# Higgs Boson Self-Coupling Measurements
# Using Ratios of Cross Sections

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Theory Seminar
Fermilab
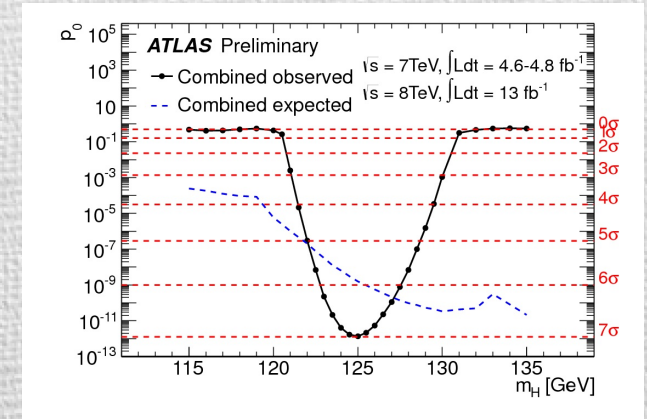May 16, 2013

# Outline

- Motivation

- Higgs-Pair Production Analysis

  ➜ Different decay channels

  ➜ Dissection of the cross section

  ➜ Theoretical Errors – Ratio of cross sections

  ➜ Variation with self coupling and top yukawa

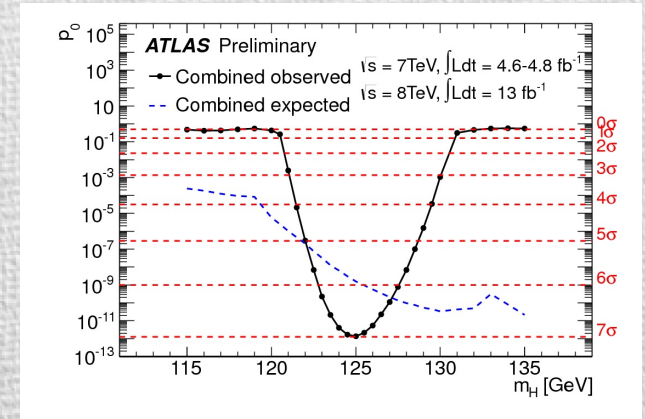- Expected Constraints on Trilinear Self Coupling
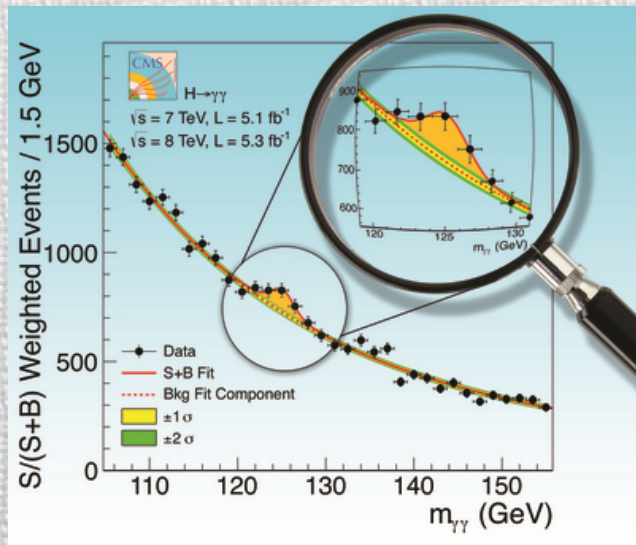
- Outlook and Conclusions
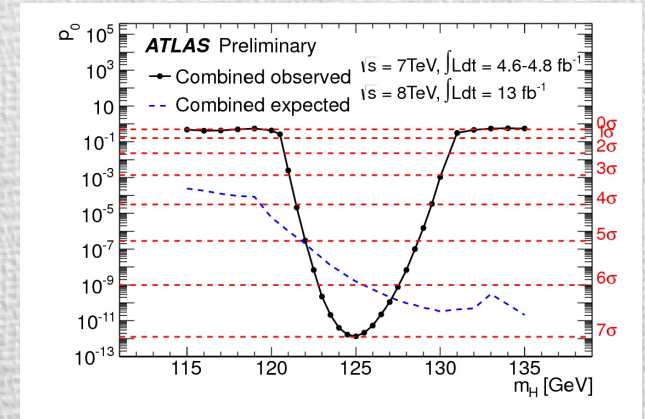
# Motivation

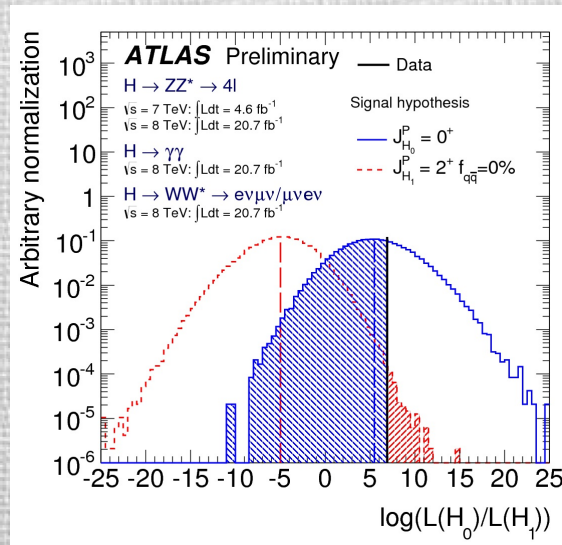# Motivation



- Have discovered a new *particle*

# Motivation

- Have discovered a new *boson*

# Motivation

- Have discovered a new *scalar*
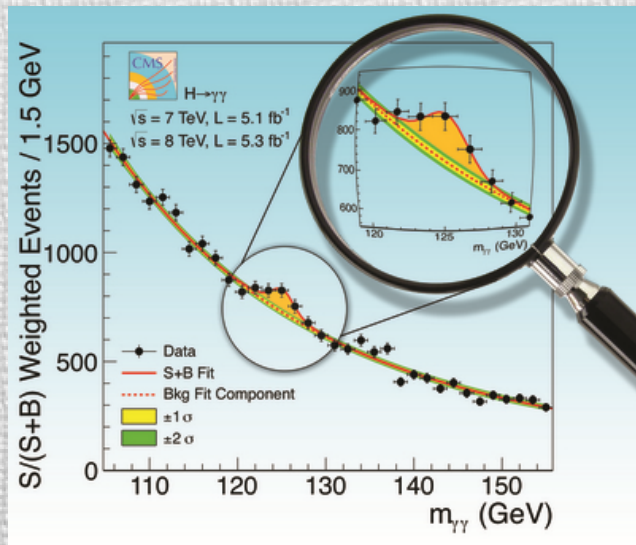
# Motivation

- ## Have discovered *a Higgs boson*
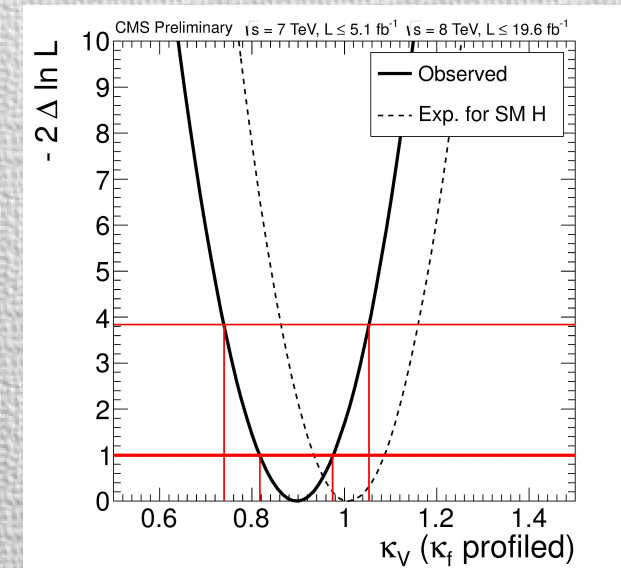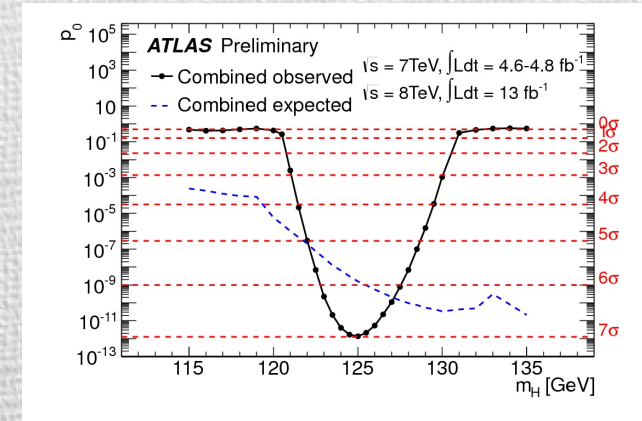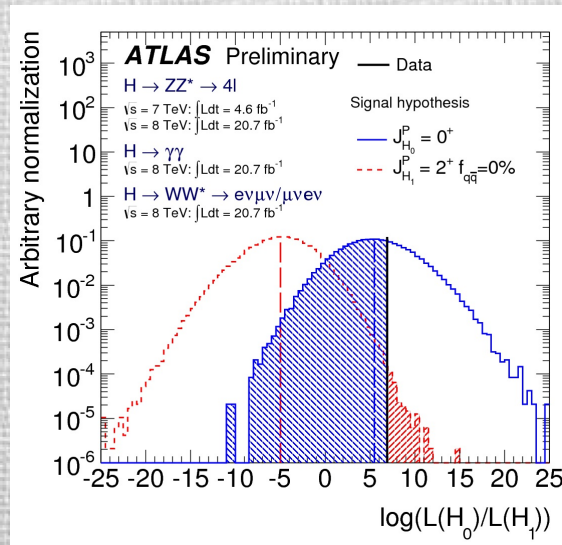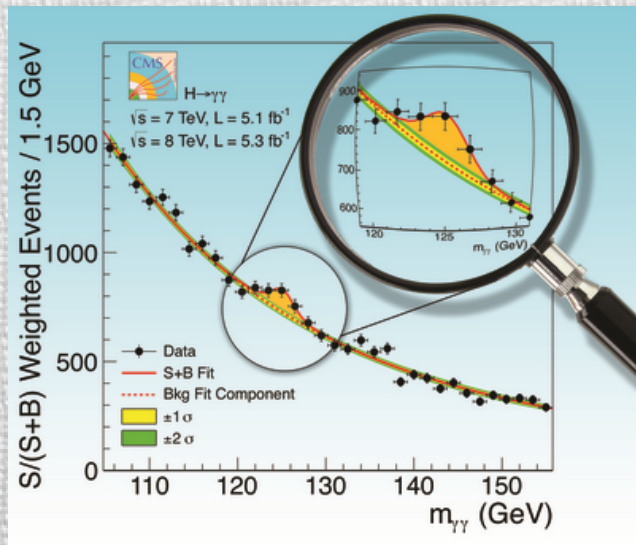
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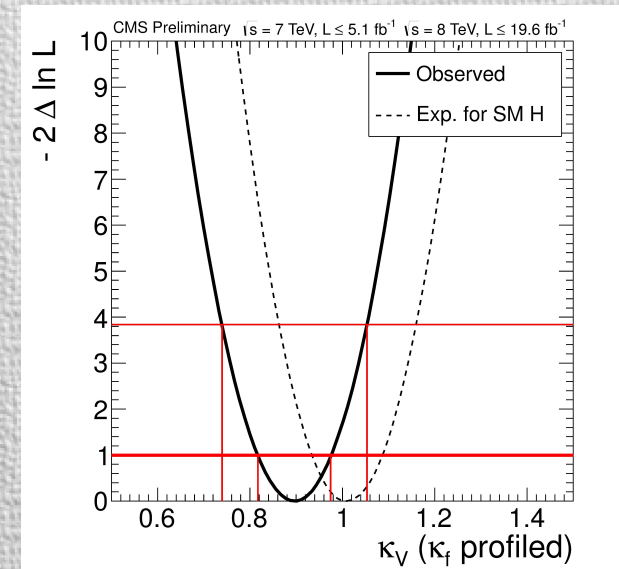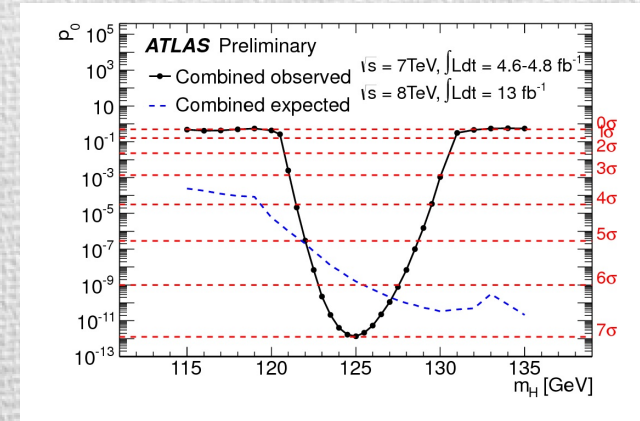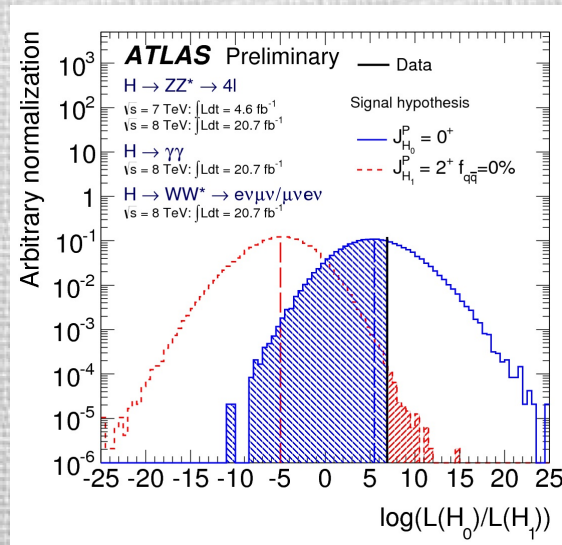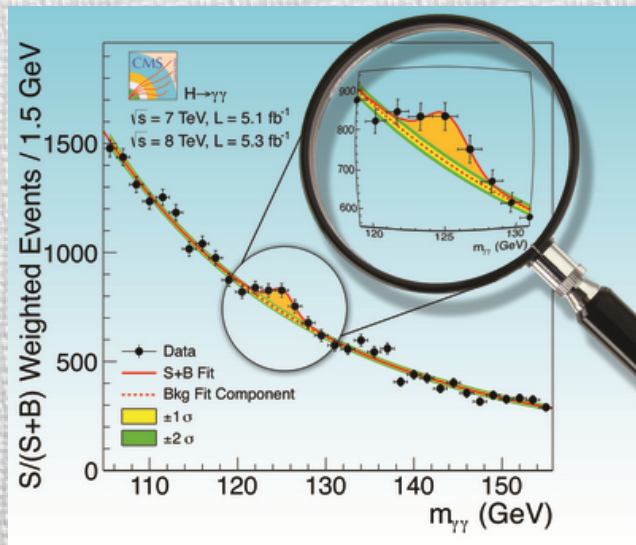


- ## Is it *the* SM-Higgs Boson?

...

# Motivation

Is it *the* SM-Higgs Boson?
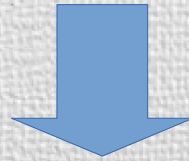
Measure further properties like decay rates to other SM fields
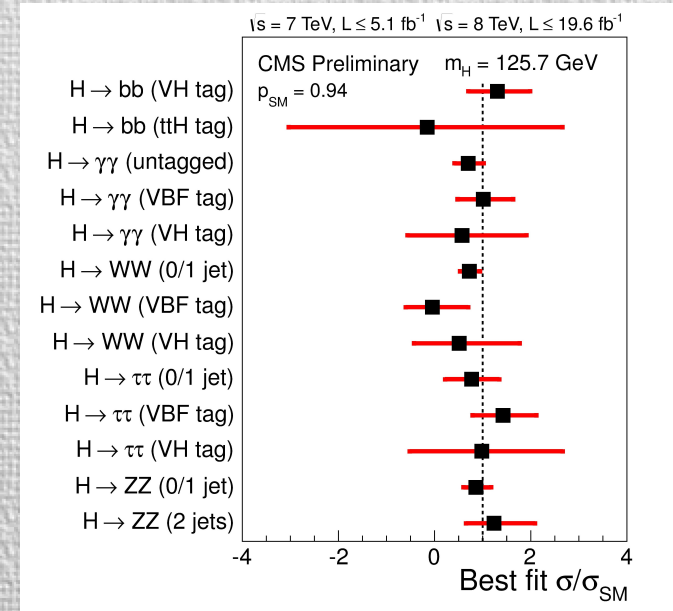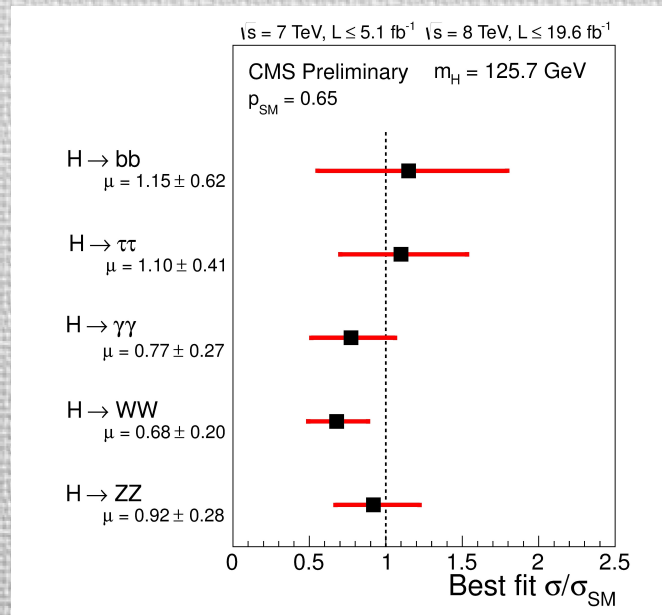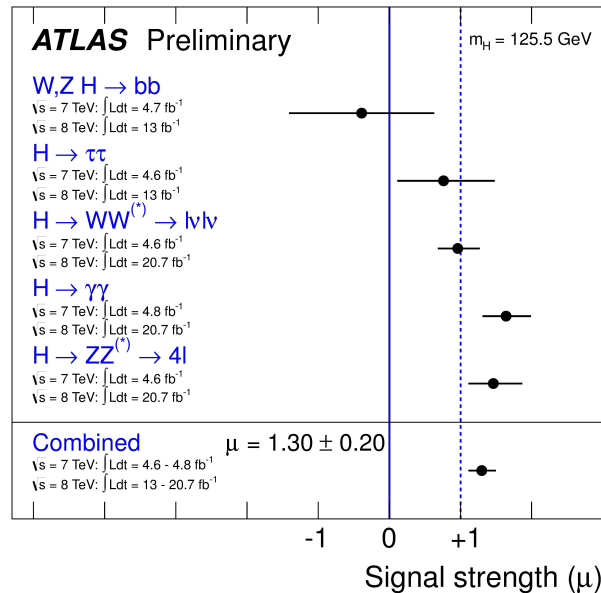
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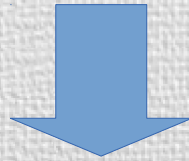
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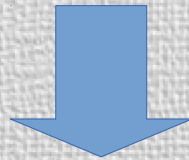
couplings

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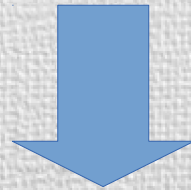
Measure self couplings!

# Motivation

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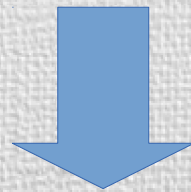
Measure self couplings!

↳ test Higgs potential

$$V(H) = \frac{1}{2} M_H^2 H^2 + \lambda_{HHH} v H^3 + \frac{1}{4} \lambda_{HHHH} H^4$$

# Motivation

Is it *the* SM-Higgs Boson?
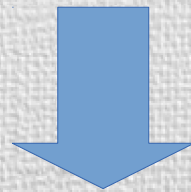
Measure self couplings!

↳ consistent with SM predictions or signs of NP?

$$V(H) = \frac{1}{2}M_H^2 H^2 + \lambda_{HHH} v H^3 + \frac{1}{4}\lambda_{HHHH} H^4$$

$$\lambda_{HHH}^{SM} = \lambda_{HHHH}^{SM} = \frac{M_H^2}{2v^2} \approx 0.13$$

# Motivation

Is it *the* SM-Higgs Boson?
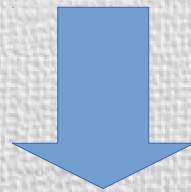
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$$V(H) = \frac{1}{2}M_H^2 H^2 + \lambda_{HHH} v H^3 + \frac{1}{4}\lambda_{HHHH} H^4$$

$M_H \simeq 125\,\mathrm{GeV}$ established @LHC
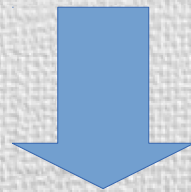
Florian Goertz          Measuring $\lambda$ using Ratios of Cross Sections

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Measure self couplings!

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$$V(H) = \frac{1}{2} M_H^2 H^2 + \lambda_{HHH} v H^3 + \frac{1}{4} \lambda_{HHHH} H^4$$

$\lambda_{HHH}$ can be measured in
*Higgs-pair production*
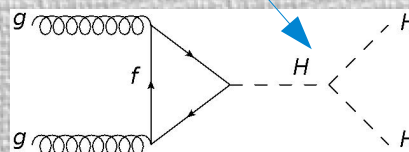
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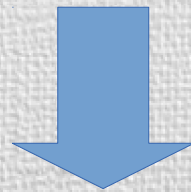
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$$V(H) = \frac{1}{2}M_H^2 H^2 + \lambda_{HHH} v H^3 + \frac{1}{4}\lambda_{HHHH} H^4$$

Triple Higgs production
-Extremeley challenging @(V)LHC
0.06 fb @ LHC14
9.45 fb @ VLHC (200 TeV)
Plehn, Rauch, hep-ph/0507321

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# Higgs-Pair Production Analysis

# Higgs-Pair Production

- Most important production mechanism: $\mathrm{gg} \to HH$
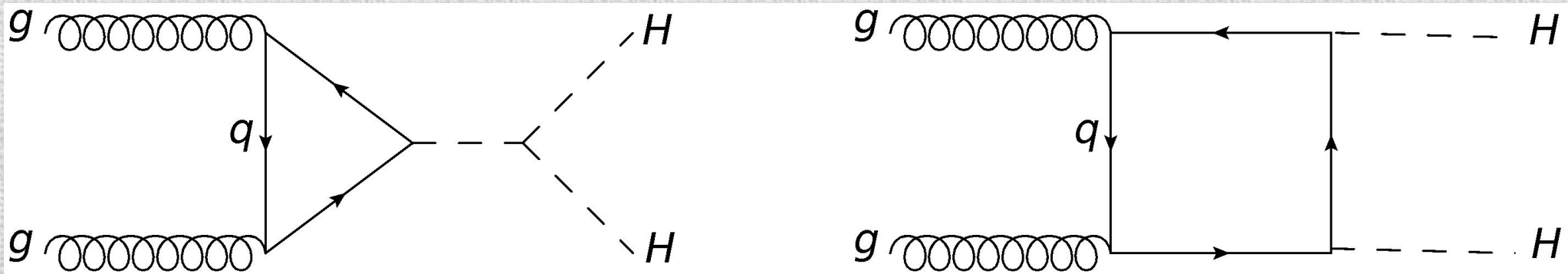
Eboli, Marques, Novaes, Natale, PLB 197(1987)269;  Glover, van der Bij, NPB 309(1988)282
Dawson, Dittmaier and M. Spira, PRD 58(1998)115012

$$\sigma(gg \to HH)_{\mathrm{LO}} \sim 17\,\mathrm{fb}$$

$$\sigma(gg \to HH)_{\mathrm{NLO}} \sim 33\,\mathrm{fb}$$

14TeV LHC
$M_H \sim 125$ GeV

Theoretical error (mostly scale variation): ~ 20% @NLO

# Higgs-Pair Production

- Other production channels $qq' \rightarrow HHqq', VHH, t\bar{t}HH$

  ~10-30 times smaller (neglect in following)
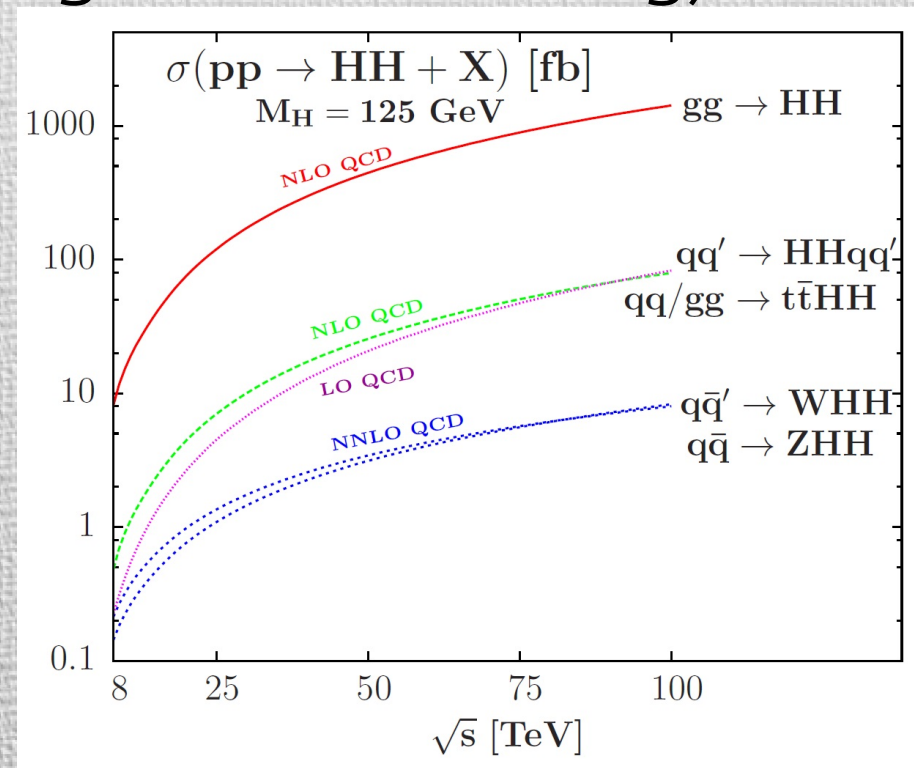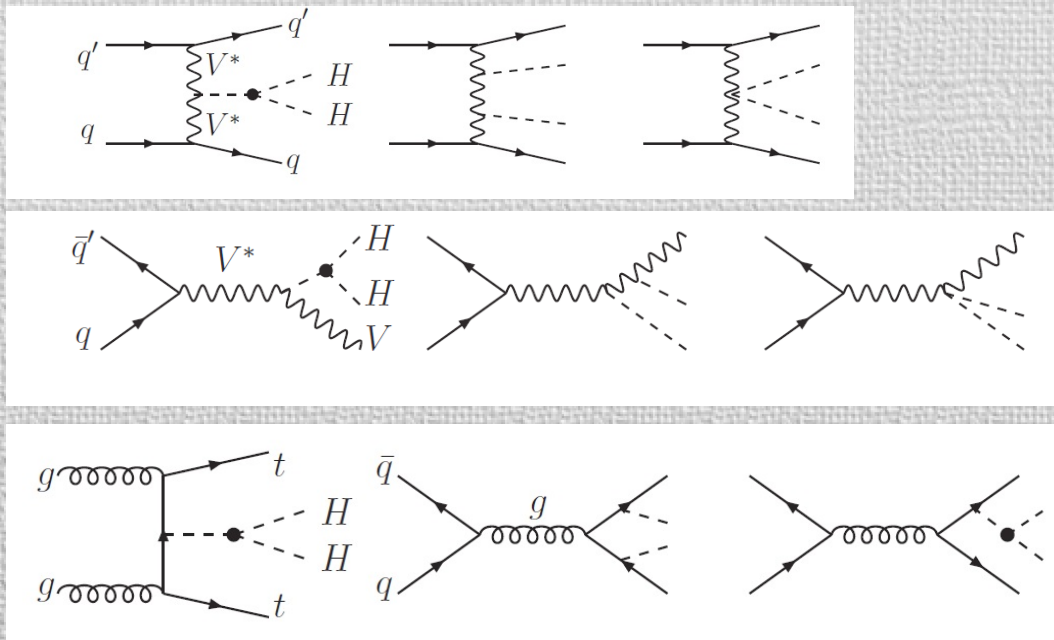


See [e.g.] Baglio, Djouadi, Grober, Muhlleitner, Quevillon, Spira, 1212.5581, and refs. therein

# Decay Channels

## Discovery potential for LHC studied in different channels
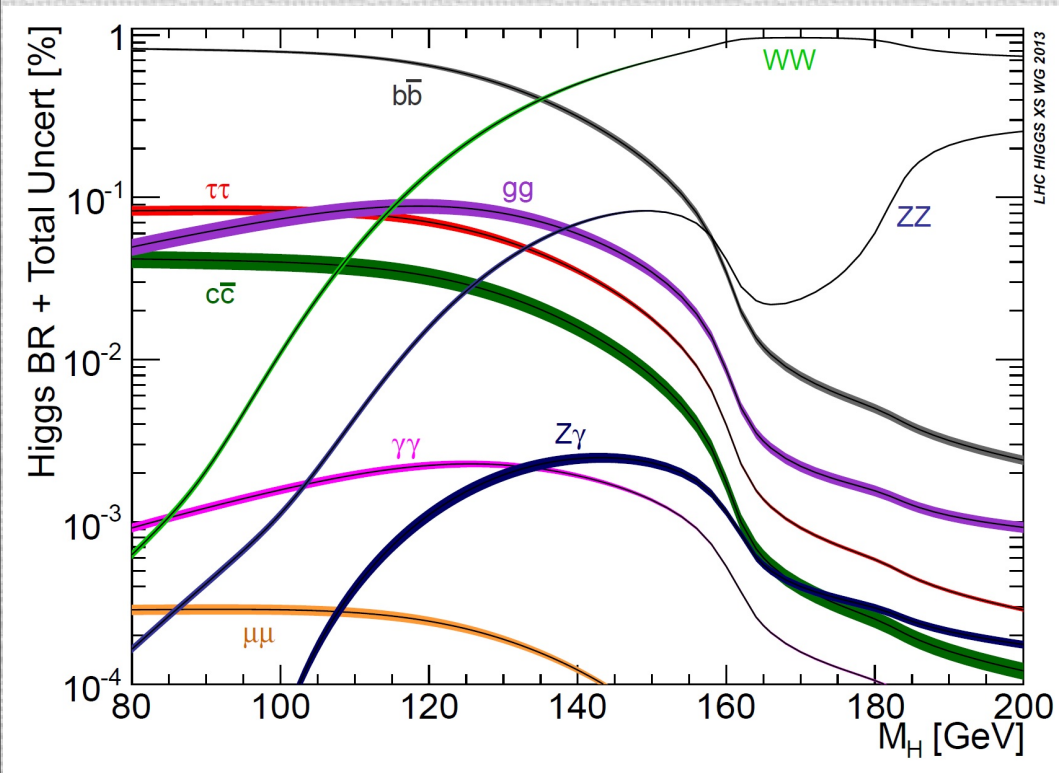


Baur, Plehn, Rainwater, hep-ph/0310056
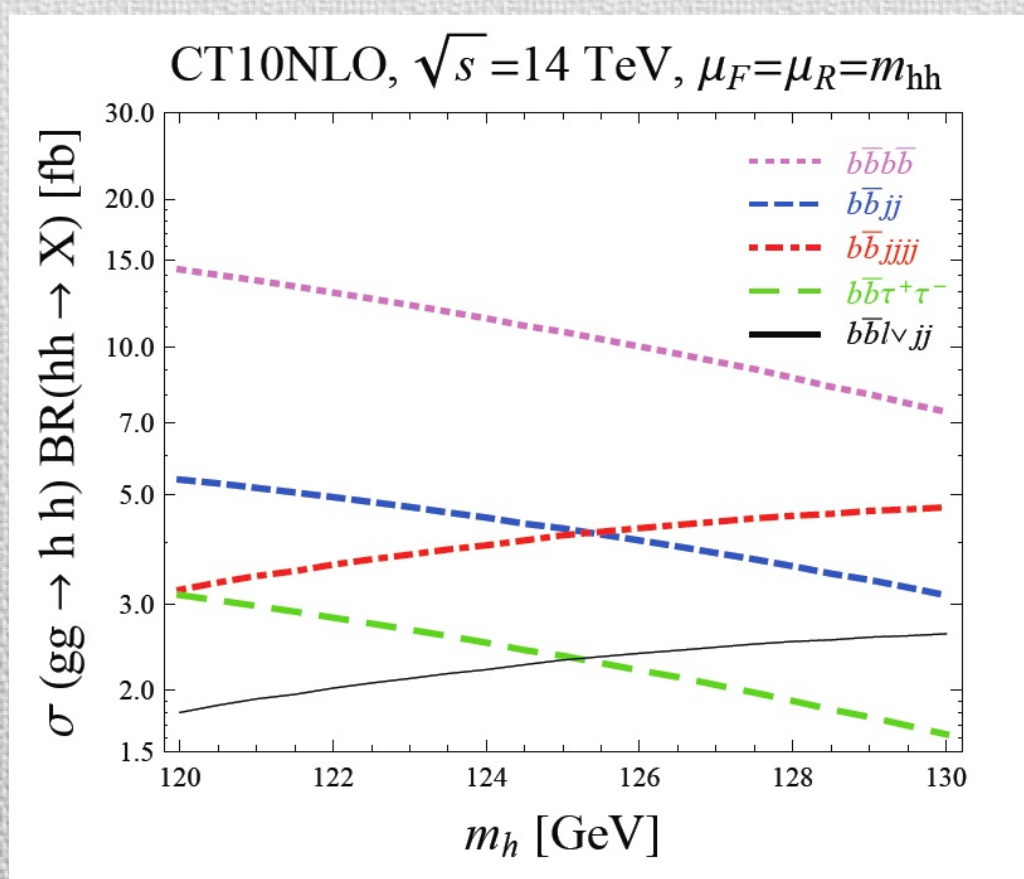


Papaefstathiou, Yang, Zurita, 1209.1489

Hadronic modes dominate

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# Decay Channels

Discovery potential for LHC studied in different channels

- Before 2008: @600fb$^{-1}$

  only $\boxed{HH \to b\bar{b}\gamma\gamma}$ promising (for M$_H$~120 GeV): S/B=6/12.5 $\Rightarrow$ $1.5\sigma$

  Baur, Plehn, Rainwater, hep-ph/0310056

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  Baur, Plehn, Rainwater, hep-ph/0310056

- After 2008:
  Boosted jet+substructure techniques

  Butterworth, Davison, Rubin, Salam, 0802.2470
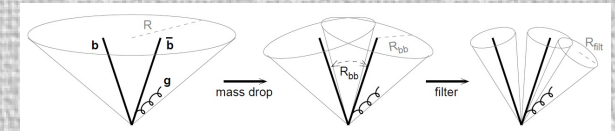
  

  $HH \rightarrow b\bar{b}\tau^+\tau^-$

  Dolan, Englert, Spannowsky, 1206.5001

  $HH \rightarrow b\bar{b}W^+W^-$

  Papaefstathiou, Yang, Zurita, 1209.1489

  S/B=57/119 $\rightarrow 4.85\,\sigma$　　　　S/B=12/8 $\rightarrow 3.3\,\sigma$

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# Decay Channels

In $b\bar{b}\gamma\gamma$ analysis, expected LHC constraints on $\lambda$ have been derived, using fits to the visible mass distribution
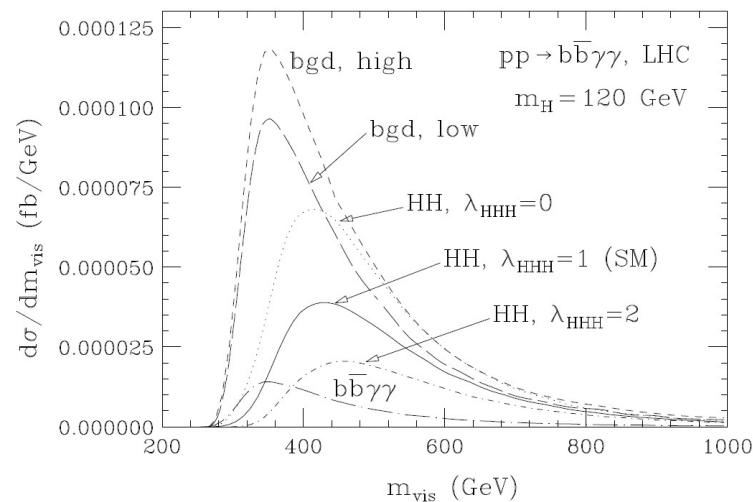


- Optimistic assumptions for background subtraction
- Need good knowledge of shapes, low number of events...

$$\text{define } \lambda \equiv \lambda_{HHH}/\lambda_{HHH}^{SM}$$

$$\lambda \in (0.26, 1.94)@\,600\,\text{fb}^{-1}, \quad \lambda \in (0.54, 1.52)@\,6000\,\text{fb}^{-1}(\text{SLHC})$$

# Decay Channels

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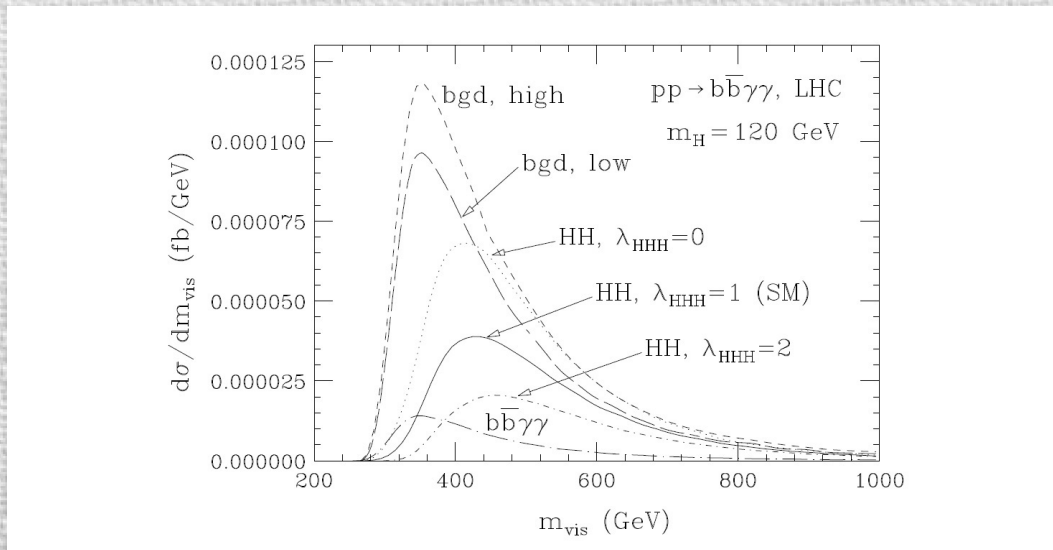


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$$\text{define } \lambda \equiv \lambda_{HHH}/\lambda_{HHH}^{SM}$$

$$\lambda \in (0.26, 1.94) @ 600\,\text{fb}^{-1}, \quad \lambda \in (0.54, 1.52) @ 6000\,\text{fb}^{-1}(\text{SLHC})$$

- In promising $b\bar{b}\tau^+\tau^-$, $b\bar{b}W^+W^-$ only established these channels for discovering HH production, no limits on $\lambda$

# Higgs-Pair Production

- In the following derive expected constraints on $\lambda$ for $M_H \sim 125$ GeV, using the most promising channels at the 14TeV LHC @600fb$^{-1}$, 3000fb$^{-1}$

- Relatively low number of signal events (or difficult final states), control shapes of backgrounds/signal?
➡ Use *total* cross section,
    try to reduce theoretical error

- Study dependence on $y_t$

# The Cross Section
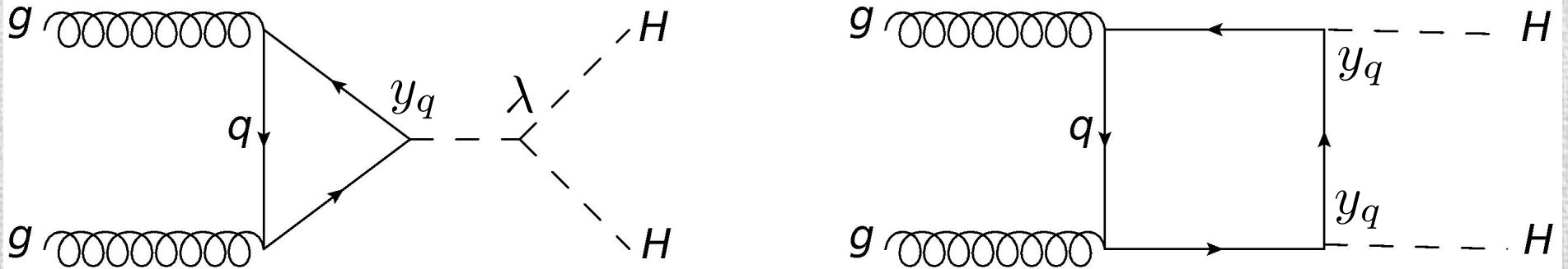


$$\sigma_{HH}^{LO} = |\sum_{q=t,b}(\alpha_q C_{q,\text{tri}}^{(1)} + \beta_q C_{q,\text{box}}^{(1)})|^2 + |\sum_{q=t,b} \gamma_q C_{q,\text{box}}^{(2)}|^2$$

In the SM: $\alpha_q = \lambda\, y_q\,, \quad \beta_q = \gamma_q = y_q^2$

# The Cross Section
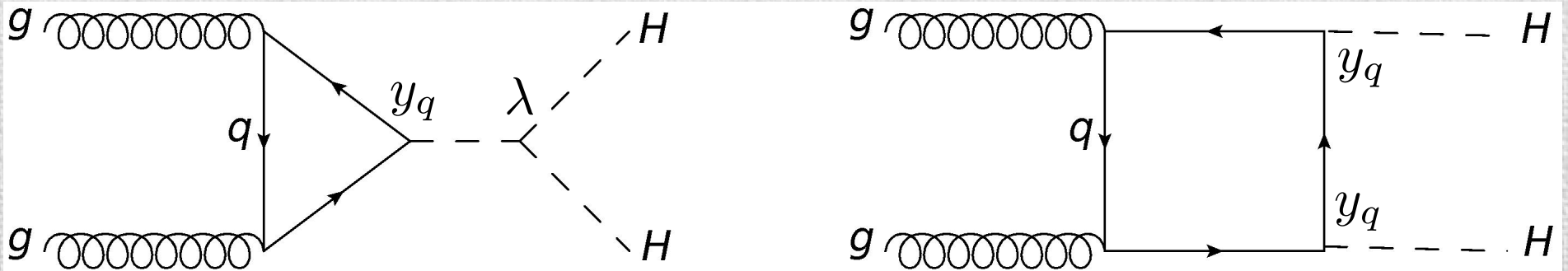


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In the SM: $\alpha_q = \lambda y_q, \quad \beta_q = \gamma_q = y_q^2$

$$\sigma_{HH}^{\text{LO}}[\text{fb}] = 5.22\lambda^2 y_t^2 - 25.1\lambda y_t^3 + 37.3 y_t^4 + \mathcal{O}(\text{y}_b \text{y}_t^2 \lambda_{HHH})$$

$$\sigma_{HH}^{\text{NLO}}[\text{fb}] = 9.66\lambda^2 y_t^2 - 46.9\lambda y_t^3 + 70.1 y_t^4 + \mathcal{O}(\text{y}_b \text{y}_t^2 \lambda_{HHH})$$

Fits obtained from `hpair, http://people.web.psi.ch/spira/hpair/`, $y_t \equiv \text{y}_t/\text{y}_t^{SM}$
using MSTW2008lo68cl and MSTW2008nlo68cl pdfs

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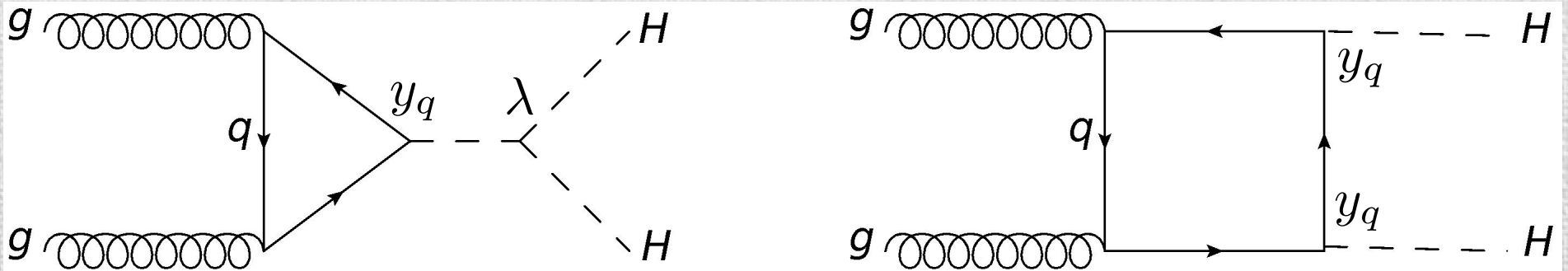
# The Cross Section



off-shell Higgs!

~0.2% effect (in SM)

$$\sigma_{HH}^{\mathrm{LO}}[\mathrm{fb}] = \quad 5.22\lambda^2 y_t^2 \ominus 25.1\lambda y_t^3 + 37.3 y_t^4 + \mathcal{O}(\mathrm{y}_b \mathrm{y}_t^2 \lambda_{HHH})$$

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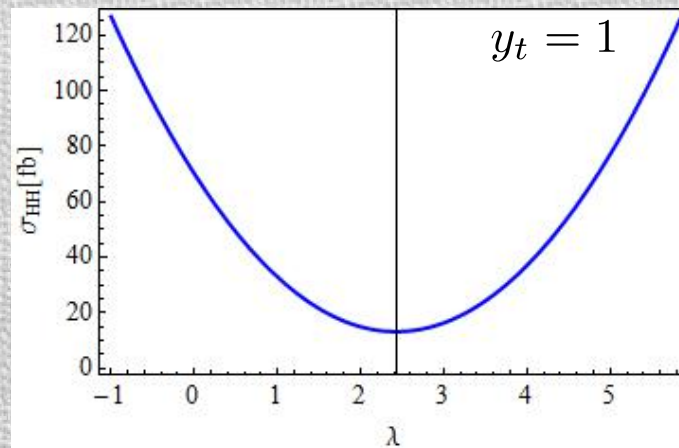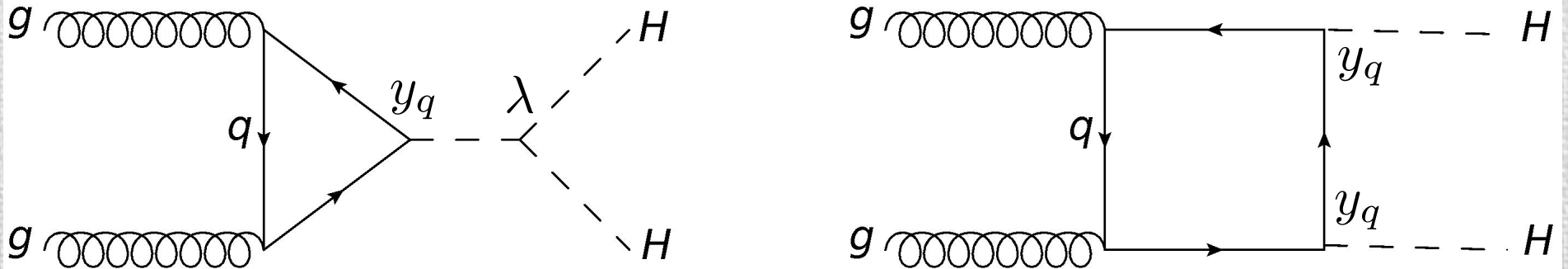
# The Cross Section



$$\lambda_{min} \approx 2.5\, y_t$$

Symmetric about minimum
Focus on $\lambda \in (-1.0, \lambda_{min})$

$$\sigma_{HH}^{\mathrm{NLO}}[\mathrm{fb}] = 9.66\lambda^2 y_t^2 - 46.9\lambda y_t^3 + 70.1 y_t^4 + \mathcal{O}(y_b y_t^2 \lambda_{HHH})$$

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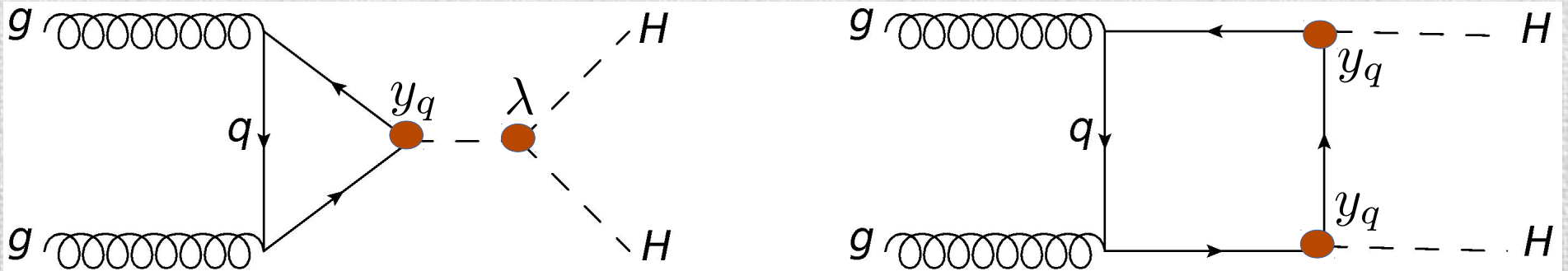


- Model dependence of analysis? Beyond consistency check of SM?

- Assume $\mathcal{L} = \mathcal{L}_{\text{SM}}$ everywhere to leading approximation besides potentially in the ($D \leq 4$) Higgs potential and the (SM-like) Yukawa couplings, where allow for $\lambda \neq 1, y_t \neq 1$

- Realized e.g. in 2HDM, Higgs-Portal models in certain parts of parameter-space

# Theoretical Errors and Ratios

- Ratio of cross sections $C_{HH} = \frac{\sigma(gg \to HH)}{\sigma(gg \to H)} \equiv \frac{\sigma_{HH}}{\sigma_H}$
  expected to be more accurately determined
  theoretically than double-Higgs cross section itself

  A. Djouadi, 1208.3436

- Both gluon-gluon initiated and expected to
  feature similar higher order QCD corrections
  (initial state gluon radiation)
  → QCD uncertainties drop out to some extent

- Check in following

$\sqrt{s} = 14$ TeV, $0.5\mu_0 < \mu < 2.0\mu_0$, LO (MSTW2008lo68cl)
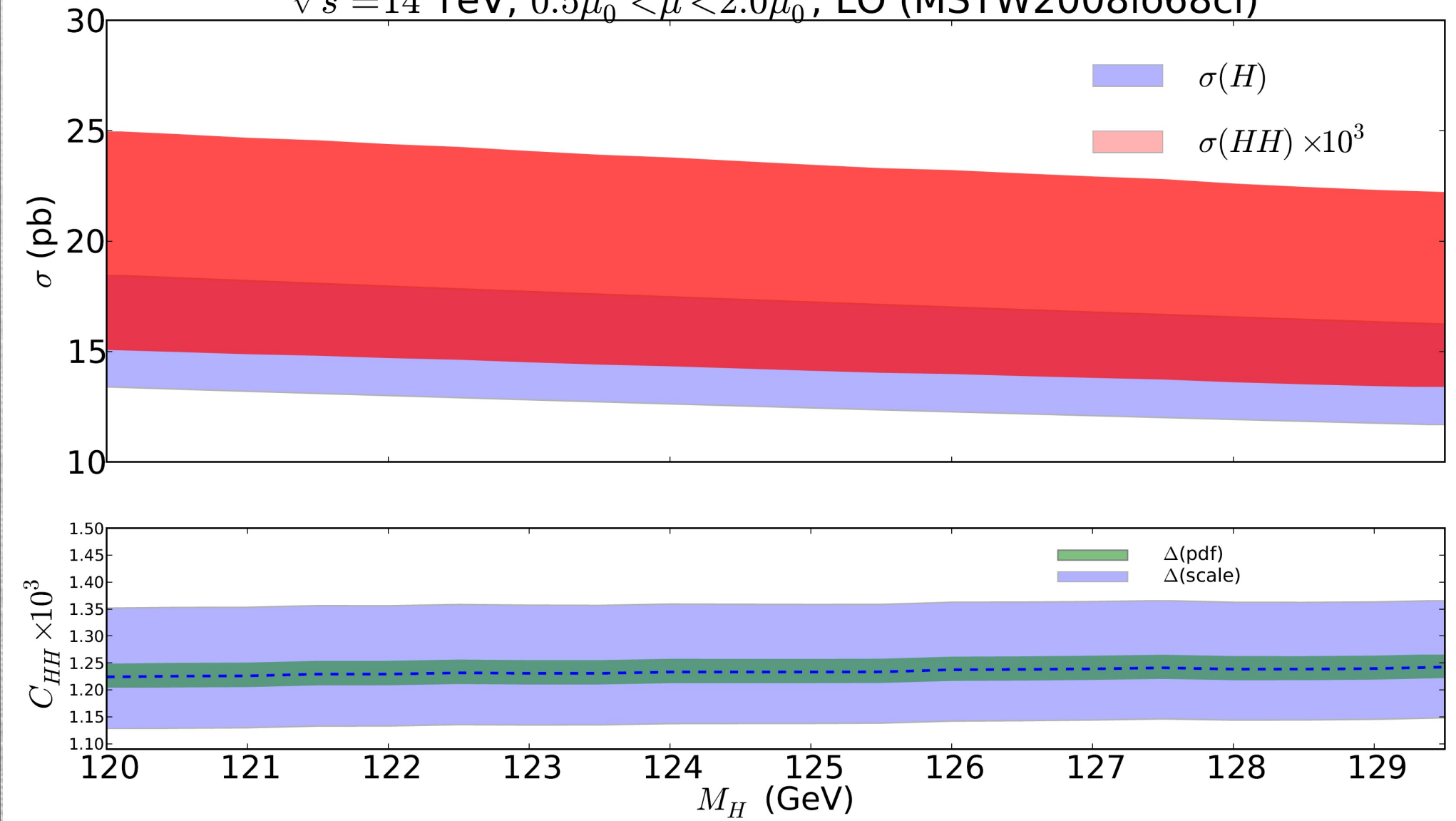
- $\sigma(H)$
- $\sigma(HH) \times 10^3$
- $\Delta(\text{pdf})$
- $\Delta(\text{scale})$

$\sigma$ (pb)

$C_{HH} \times 10^3$

$M_H$ (GeV)

used: M. Spira, *hpair*,
*HIGLU*, hep-ph/9510347

$\mu \in [0.5\mu_0, 2\mu_0]$
$\mu_0 = M_H(M_{HH})$

(similar results if $M_{HH} \to M_H$)

- Error due to scale variation significantly reduced in ratio

$$\Delta_{\sigma^{\text{LO}}} = \pm(20 - 25)\% \to \Delta_{C_{HH}^{\text{LO}}} \simeq \pm 9\%$$

$\sqrt{s} = 14$ TeV, $0.5\mu_0 < \mu < 2.0\mu_0$, NLO (MSTW2008nlo68cl)
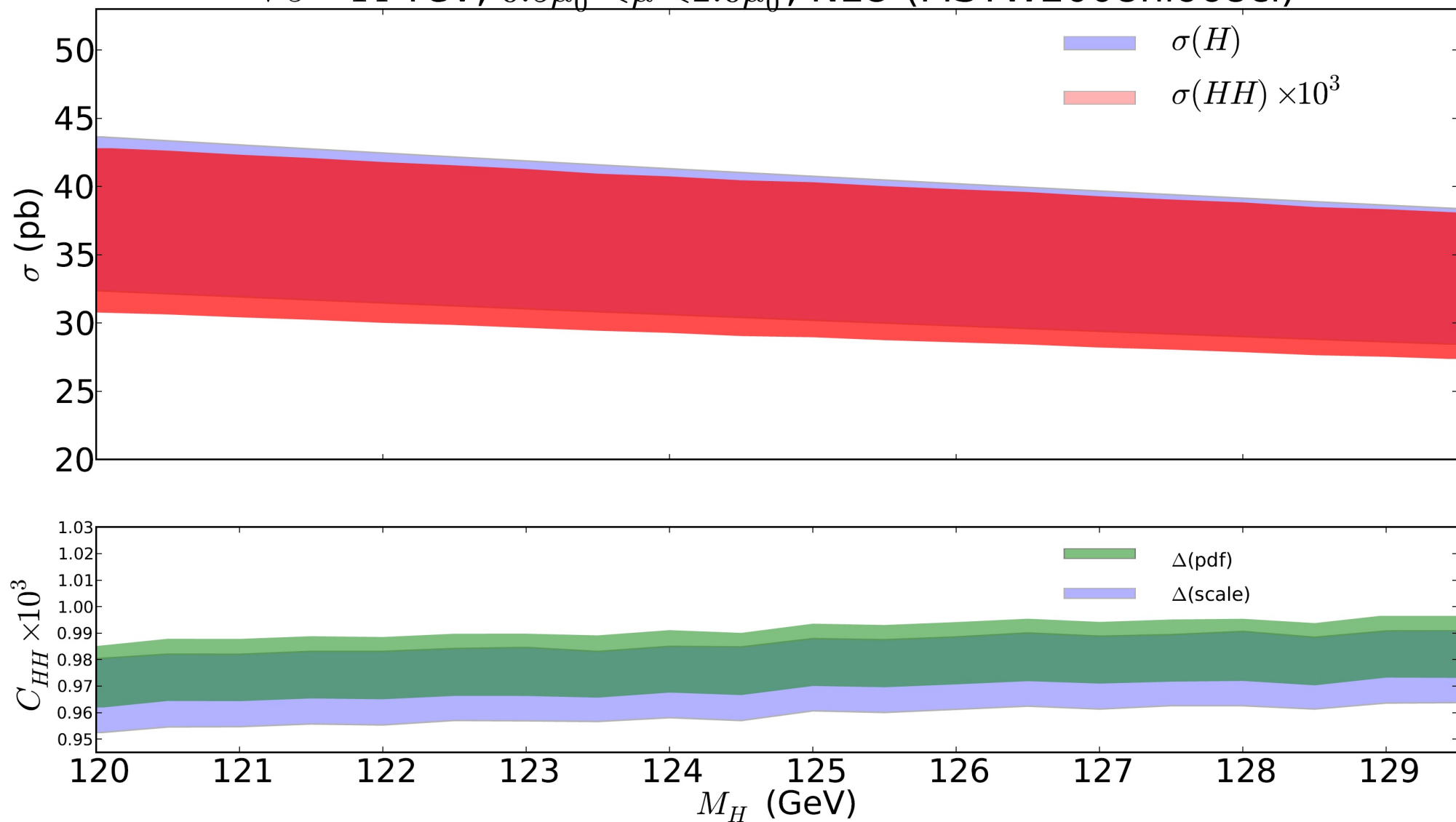
Legend (top panel): $\sigma(H)$, $\sigma(HH) \times 10^3$

Legend (bottom panel): $\Delta(\text{pdf})$, $\Delta(\text{scale})$

Axis labels: $\sigma$ (pb), $C_{HH} \times 10^3$, $M_H$ (GeV)

used: M. Spira, `hpair`, `HIGLU`, hep-ph/9510347

$\mu \in [0.5\mu_0, 2\mu_0]$
$\mu_0 = M_H(M_{HH})$

(similar results if $M_{HH} \to M_H$)

• Error due to scale variation significantly reduced in ratio

$$\Delta_{\sigma^{\text{NLO}}}^{\text{scale}} \simeq \pm 17\% \to \Delta_{C_{HH}^{\text{NLO}}}^{\text{scale}} \simeq \pm 1.5\%$$

Figure top-left: $\sqrt{s} = 14$ TeV, $0.5\mu_0 < \mu < 2.0\mu_0$, LO (MSTW2008lo68cl), with $\sigma(H)$ and $\sigma(HH) \times 10^3$, axes $\sigma$ (pb) vs $M_H$ (GeV), and lower panel $C_{HH} \times 10^3$ with $\Delta(\text{pdf})$ and $\Delta(\text{scale})$.

Figure top-right: $\sqrt{s} = 14$ TeV, $0.5\mu_0 < \mu < 2.0\mu_0$, NLO (MSTW2008nlo68cl), with $\sigma(H)$ and $\sigma(HH) \times 10^3$, axes $\sigma$ (pb) vs $M_H$ (GeV), and lower panel $C_{HH} \times 10^3$ with $\Delta(\text{pdf})$ and $\Delta(\text{scale})$.
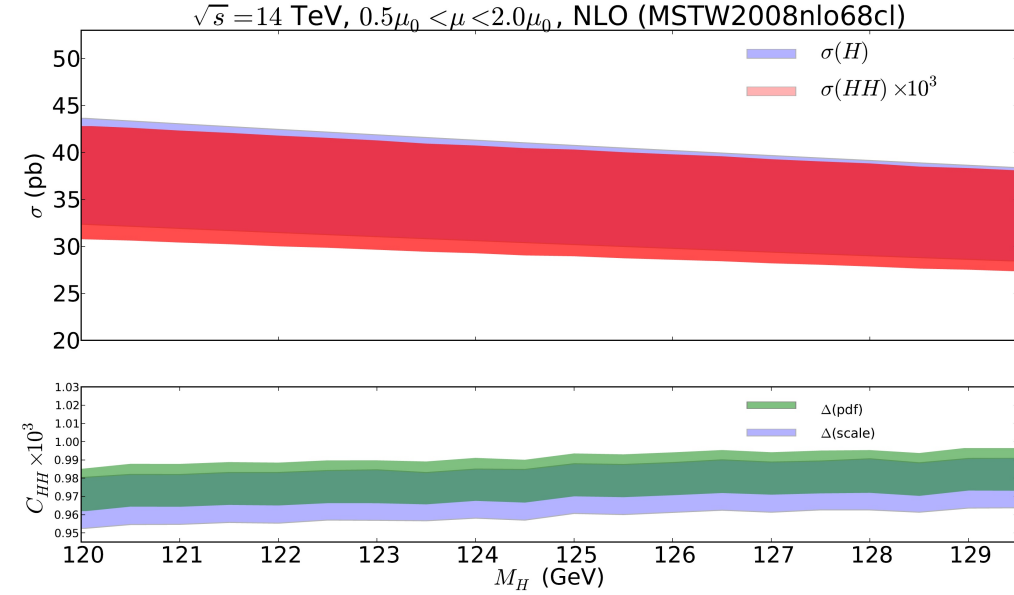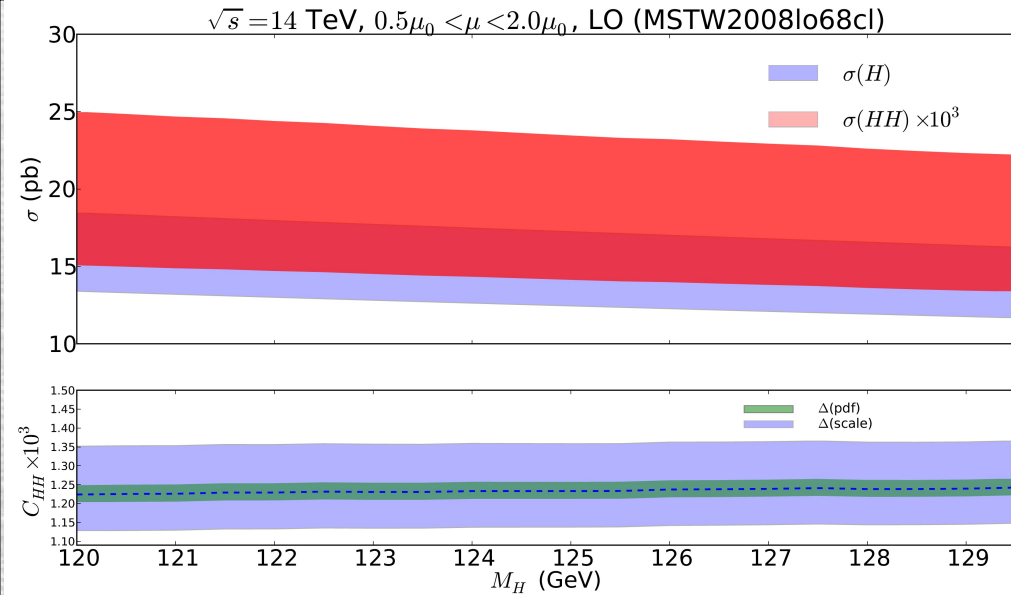
- Verification that uncertainty due to the QCD corrections (partially) cancels: K-factors in the individual cross sections are large, but also very similar ~2

  ⇨ Central value of the ratio only decreases by small amount from LO (~1.25 ) to NLO (~1.0)

- Indication that higher order corrections (NNLO) are likely to change ratio by an even smaller fraction, whereas single Higgs production cross section has K-factor of ~1.5 when compared to NLO

  LHC Higgs Cross Section Working Group, 1101.0593

- Supports reduced size of theoretcial error found in scale variation

Plot titles: $\sqrt{s} = 14$ TeV, $0.5\mu_0 < \mu < 2.0\mu_0$, LO (MSTW2008lo68cl) and $\sqrt{s} = 14$ TeV, $0.5\mu_0 < \mu < 2.0\mu_0$, NLO (MSTW2008nlo68cl)
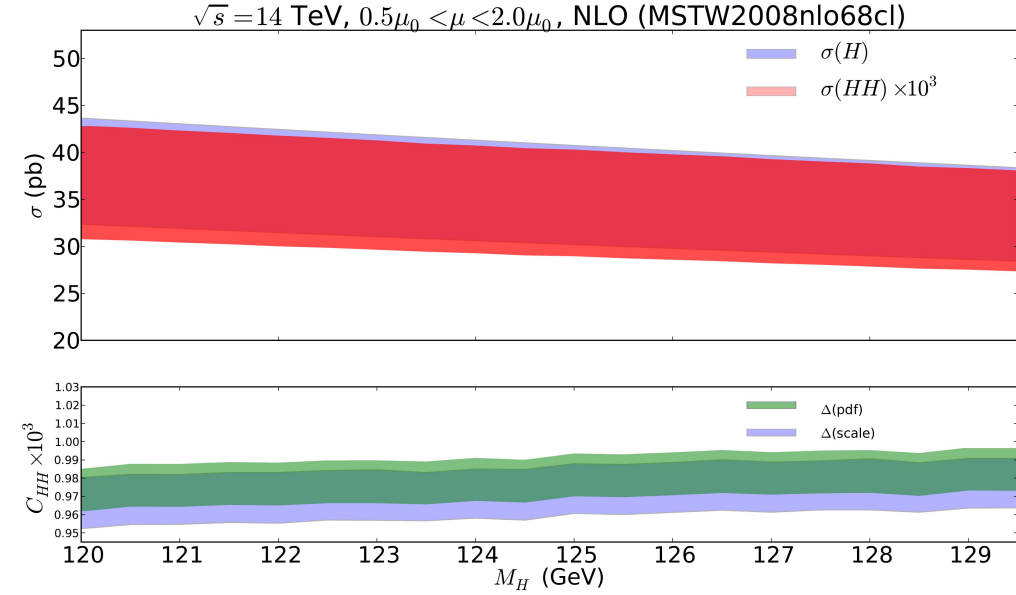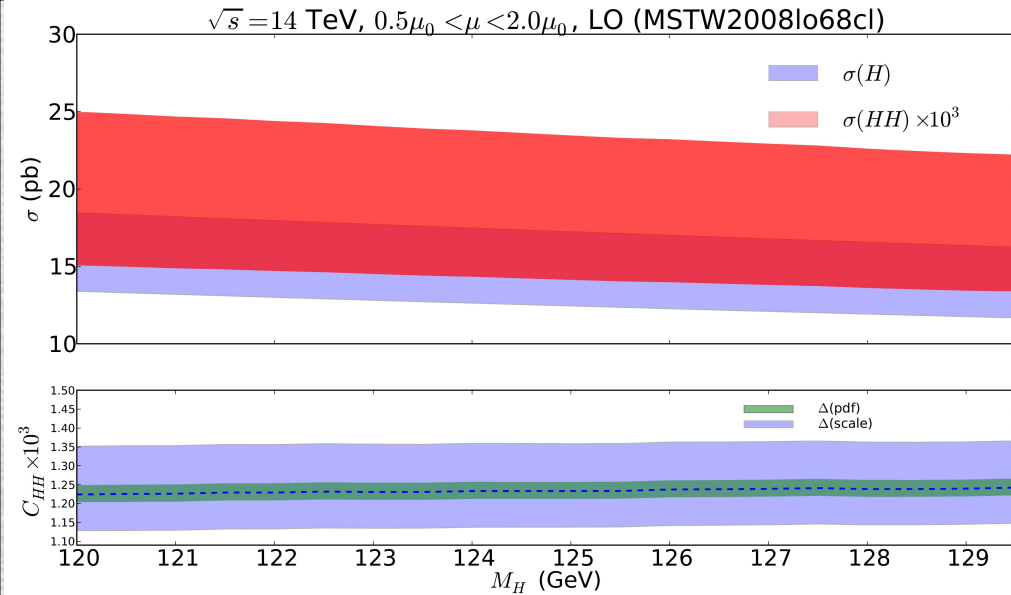
- Combining scale variation and pdf errors in quadrature

$$\Rightarrow \Delta_{C_{HH}^{\mathrm{NLO}}} \sim \mathcal{O}(\pm 3\%)$$

<span style="color:green">see also Shao, Li, Li, Wang for threshold resummation in SCET</span>

- To be compared with $\Delta_{\sigma_{HH}^{\mathrm{NLO}}} \simeq \pm 17\%$

- Conservative assumption for the following:

$$\Delta_{C_{HH}^{\mathrm{NLO}}} = \pm 5\% \,, \quad \Delta_{\sigma_{HH}^{\mathrm{NLO}}} = \pm 20\%$$

# Variation with Self-Coupling and Top-Quark Yukawa



$y_t = 1$, $M_H = 125$ GeV, LHC@14 TeV, MSTW2008nlo68cl
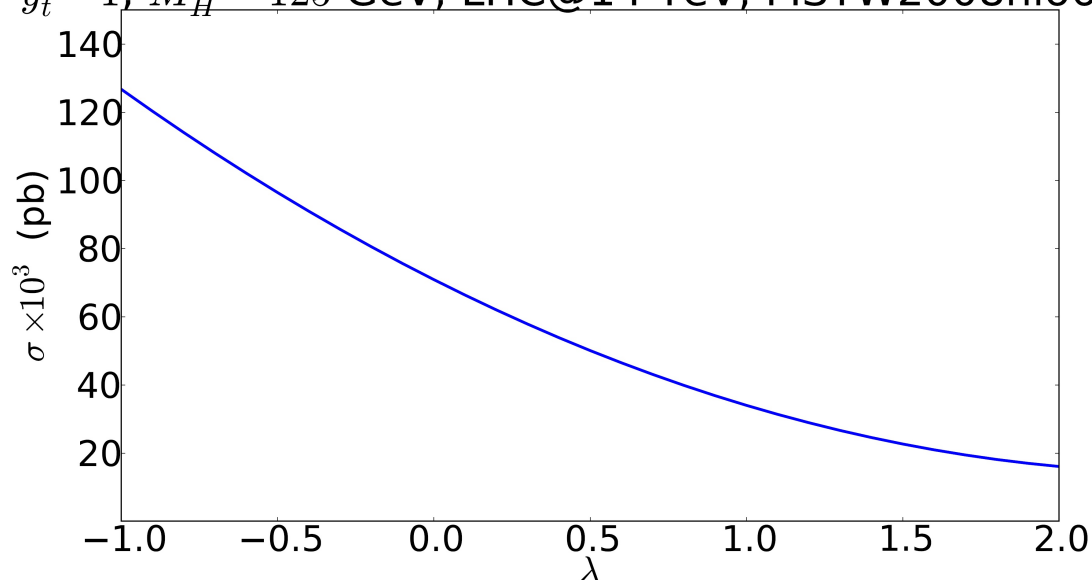
- Negative values of $\lambda$ can be excluded sooner



$y_t = 1$, $M_H = 125$ GeV, LHC@14 TeV, MSTW2008nlo68cl

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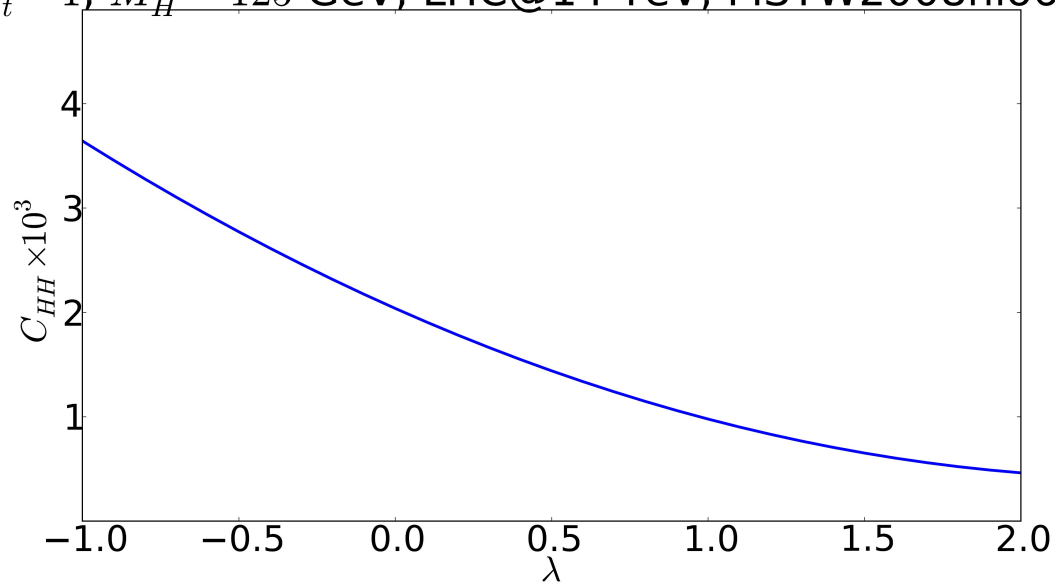
# Variation with Self-Coupling and Top-Quark Yukawa

$\lambda = 1$, $M_H = 125$ GeV, LHC@14 TeV, MSTW2008nlo68cl
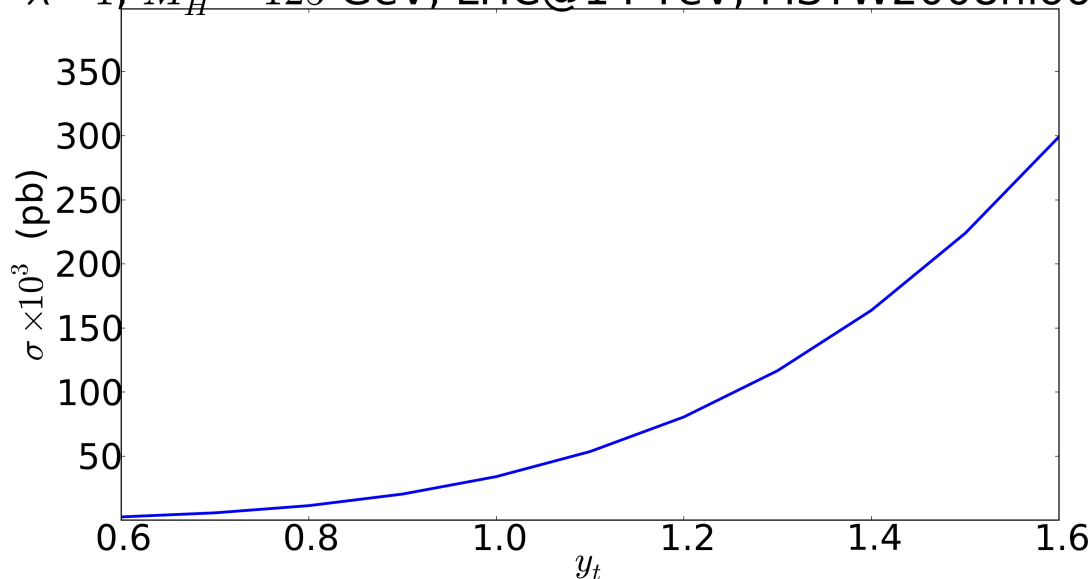


- Strong variation with top yukawa
- … which is only expected to be known up to 15% at LHC after 300fb$^{-1}$ @14 TeV Peskin, 1207.2516

$$y_t \rightarrow -y_t \text{ via } \lambda \rightarrow -\lambda$$

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$\lambda = 1$, $M_H = 125$ GeV, LHC@14 TeV, MSTW2008nlo68cl
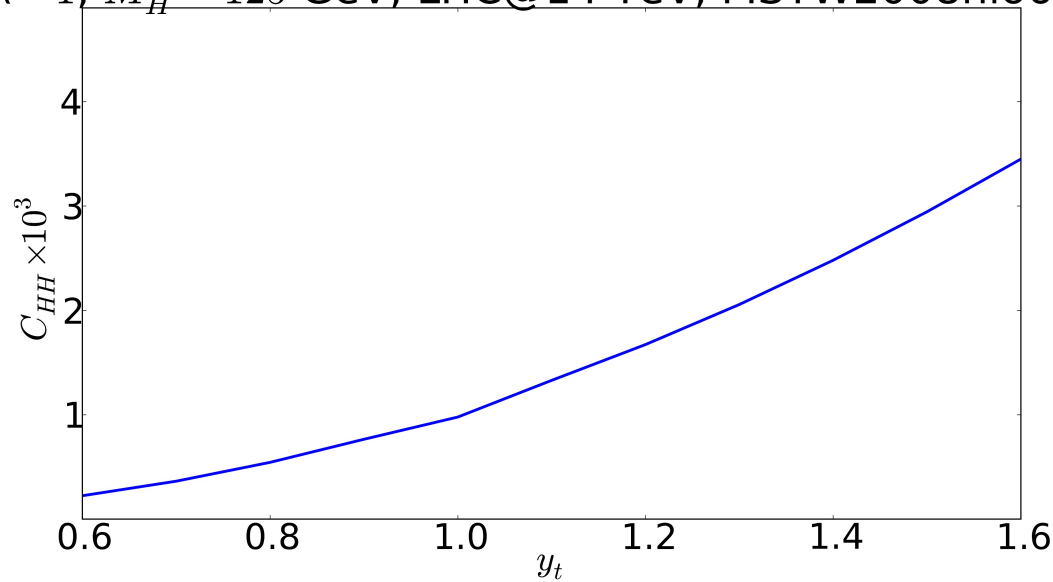
# Expected Constraints on Trilinear Self Coupling

# Constraining the Self-Coupling

- Use theoretically more stable ratio of cross sections $C_{HH}$ to derive expected constraints on $\lambda$

- Furter benefit when using $C_{HH}$ :

  Experimental uncertainties can also be reduced, e.g. some systematic uncertainties are expected to cancel (Luminosit uncertainty)

# Assumptions for Experimental Uncertainties

$$\sigma_{HH}^{b\bar{b}xx} \equiv 2\,\sigma_{HH} \times \text{BR}(b\bar{b}) \times \text{BR}(xx)$$

$$\sigma_{H}^{b\bar{b}} \equiv \sigma_{H} \times \text{BR}(b\bar{b})$$

$$C_{HH}^{\text{exp.}} = \left.\frac{\sigma_{HH}^{b\bar{b}xx}}{\sigma_{H}^{b\bar{b}} \times BR(xx)}\right|_{\text{exp.}}$$

$$\left(\frac{\Delta C_{HH}}{C_{HH}}\right)^2 = \left(\frac{\Delta\sigma_{HH}^{b\bar{b}xx}}{\sigma_{HH}^{b\bar{b}xx}}\right)^2 + \left(\frac{\Delta\text{BR}(xx)}{\text{BR}(xx)}\right)^2 + \left(\frac{\Delta\sigma_{H}^{b\bar{b}}}{\sigma_{H}^{b\bar{b}}}\right)^2$$

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# Assumptions for Experimental Uncertainties

$$\sigma_{HH}^{b\bar{b}xx} \equiv 2\,\sigma_{HH} \times \mathrm{BR}(b\bar{b}) \times \mathrm{BR}(xx)$$

$$\sigma_{H}^{b\bar{b}} \equiv \sigma_{H} \times \mathrm{BR}(b\bar{b})$$

$$C_{HH}^{\mathrm{exp.}} = \left.\frac{\sigma_{HH}^{b\bar{b}xx}}{\sigma_{H}^{b\bar{b}} \times BR(xx)}\right|_{\mathrm{exp.}}$$

$$\left(\frac{\Delta C_{HH}}{C_{HH}}\right)^2 = \left(\frac{\Delta\sigma_{HH}^{b\bar{b}xx}}{\sigma_{HH}^{b\bar{b}xx}}\right)^2 + \left(\frac{\Delta\mathrm{BR}(xx)}{\mathrm{BR}(xx)}\right)^2 + \left(\frac{\Delta\sigma_{H}^{b\bar{b}}}{\sigma_{H}^{b\bar{b}}}\right)^2$$

Add 5% theoretical error in quadrature

Actually better to access than error on BR alone, which enters the cross section itself

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Measuring $\lambda$ using Ratios of Cross Sections

# Assumptions for Experimental Uncertainties

$$\left(\frac{\Delta C_{HH}}{C_{HH}}\right)^2 = \left(\frac{\Delta\sigma_{HH}^{b\bar{b}xx}}{\sigma_{HH}^{b\bar{b}xx}}\right)^2 + \left(\frac{\Delta\mathrm{BR}(xx)}{\mathrm{BR}(xx)}\right)^2 + \left(\frac{\Delta\sigma_{H}^{b\bar{b}}}{\sigma_{H}^{b\bar{b}}}\right)^2$$

$\Delta\sigma_{HH}^{b\bar{b}xx}/\sigma_{HH}^{b\bar{b}xx}$ obtained from $b\bar{b}\tau^+\tau^-$ $b\bar{b}W^+W^-$ $b\bar{b}\gamma\gamma$ analyses via $\Delta S = \sqrt{N+B}$ after bringing channels to equal footing

$$\Delta\sigma_{H}^{b\bar{b}} \sim \pm 20\%$$
$$\Delta\mathrm{BR}(\tau^+\tau^-) \sim \pm 12\%$$
$$\Delta\mathrm{BR}(W^+W^-) \sim \pm 12\%$$
$$\Delta\mathrm{BR}(\gamma\gamma) \sim \pm 16\%$$

„European Strategy for Particle Physics"
https://indico.cern.ch/contributionDisplay.py?
contribId=144&confId=175067, 2012

Assume no improvement beyond 300 fb$^{-1}$

| Process | S/B(600 fb$^{-1}$) | $\Delta C_{HH}/C_{HH}$ (600 fb$^{-1}$) | $\Delta C_{HH}/C_{HH}$ (3000 fb$^{-1}$) |
|---|---|---|---|
| $b\bar{b}\tau^+\tau^-$ | 50/104 | 0.400 | 0.279 |
| $b\bar{b}W^+W^-$ | 11.2/7.4 | 0.513 | 0.314 |
| $b\bar{b}\gamma\gamma$ | 6/12.5 | 0.964 | 0.490 |

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# Deriving Constraints

- We now want to use $C_{HH}$ to constrain the parameters $\{p_i\}$ of a model

- Expected exclusion in parameter-space depends on true parameters of the model

# Deriving Constraints – General Strategy

- Calculate $C_{HH}$ as a function of the set of parameters {p$_i$} (e.g. new couplings/Wilson coefficients, masses) as well as theoretical error

- Estimate expected experimental errors arising from measurements of components that comprise $C_{HH}^{\text{exp.}}$

# Deriving Constraints – General Strategy

- Calculate $C_{HH}$ as a function of the set of parameters {p$_i$} (e.g. new couplings/Wilson coefficients, masses) as well as theoretical error

- Estimate expected experimental errors arising from measurements of components that comprise $C_{HH}^{\text{exp.}}$

- <u>Question to address:</u> Given an assumption for the 'true' values of the model parameters, what is the constraint we *expect* to impose on the parameters through Higgs-pair production?

# Deriving Constraints

- In the following: simplified framework $\{p_i\} = \{\lambda, y_t\}$

- Start with assuming $y_t = y_{t,\text{true}} = 1$

- Draw curves of $\lambda$ that lead to a theoretically predicted cross section of one or two standard deviations away from the true cross section, derived with the underlying true $\lambda_{\text{true}}$

- In the following focus on $\lambda \in (-1.0, \lambda_{min} \sim 2.5)$

# Deriving Constraints



$b\bar{b}\tau^{+}\tau^{-}$ channel, $y_t = 1$, $M_H = 125$ GeV, LHC@14 TeV, MSTW2008nlo68cl

SM

$C_{HH}$
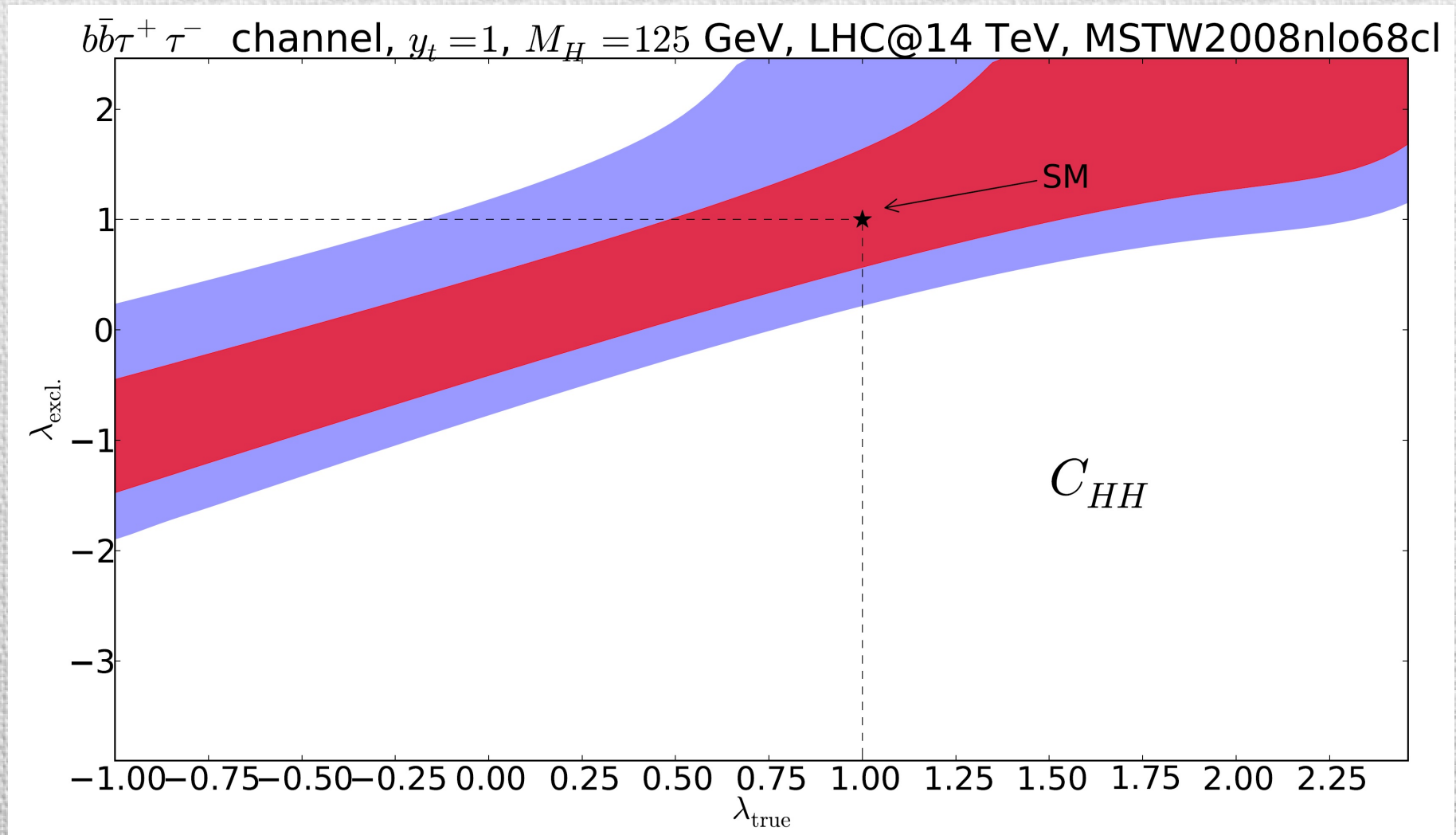
Expect to exclude values outside regions at $1\sigma$ $(2\sigma)$

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# Deriving Constraints



$b\bar{b}\tau^+\tau^-$ channel, $y_t = 1$, $M_H = 125$ GeV, LHC@14 TeV, MSTW2008nlo68cl

SM

$C_{HH}$
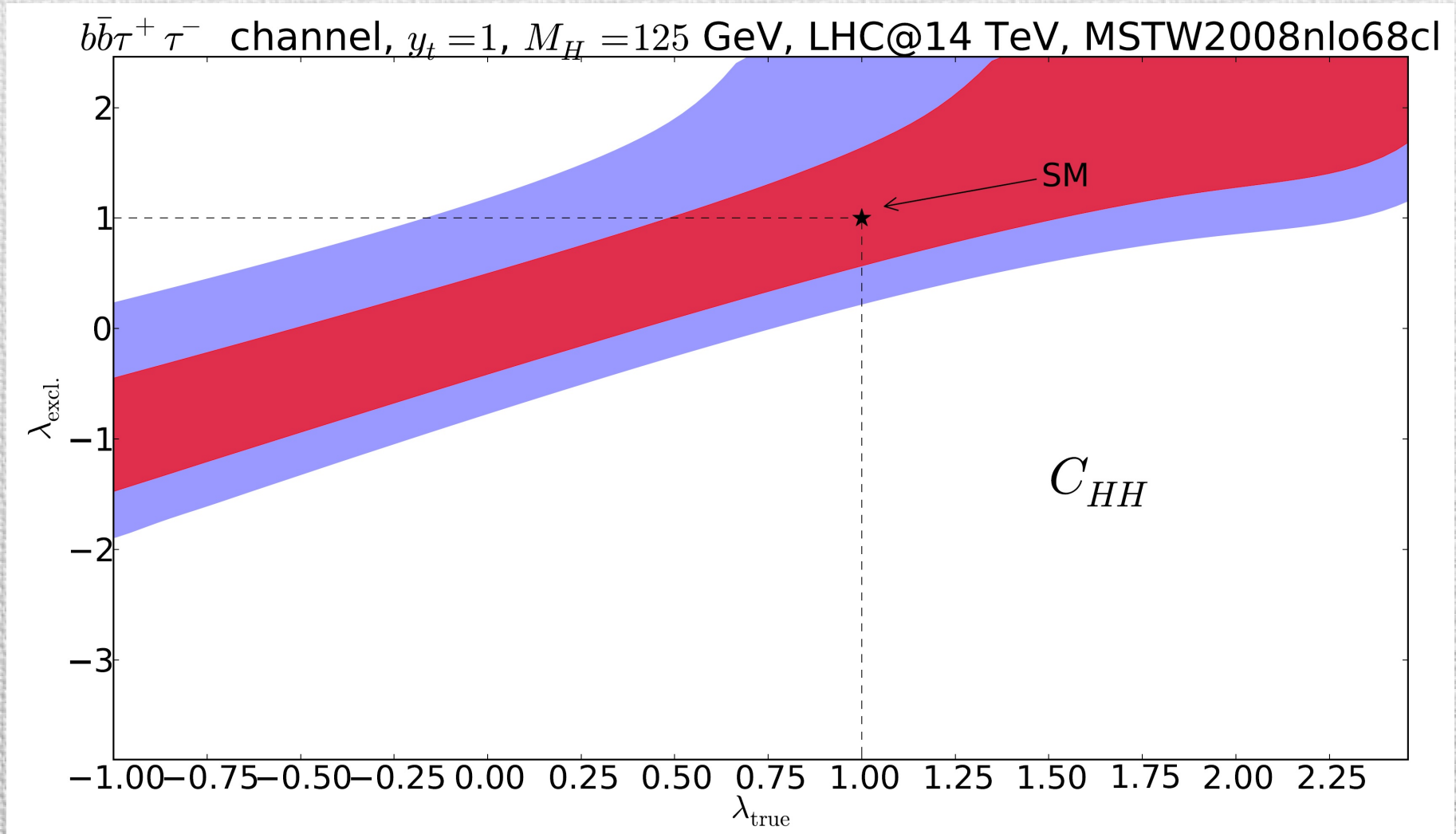
e.g. $\lambda_{\text{true}} = 1 \Rightarrow$ expect to constrain $\lambda \in (0.57, 1.64)$ @ 68%CL $(600\,\text{fb}^{-1})$

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# Deriving Constraints



$b\bar{b}\tau^+\tau^-$ channel, $y_t = 1$, $M_H = 125$ GeV, LHC@14 TeV, MSTW2008nlo68cl

SM

$\sigma_{HH}$

$\lambda_{\text{excl.}}$

$\lambda_{\text{true}}$
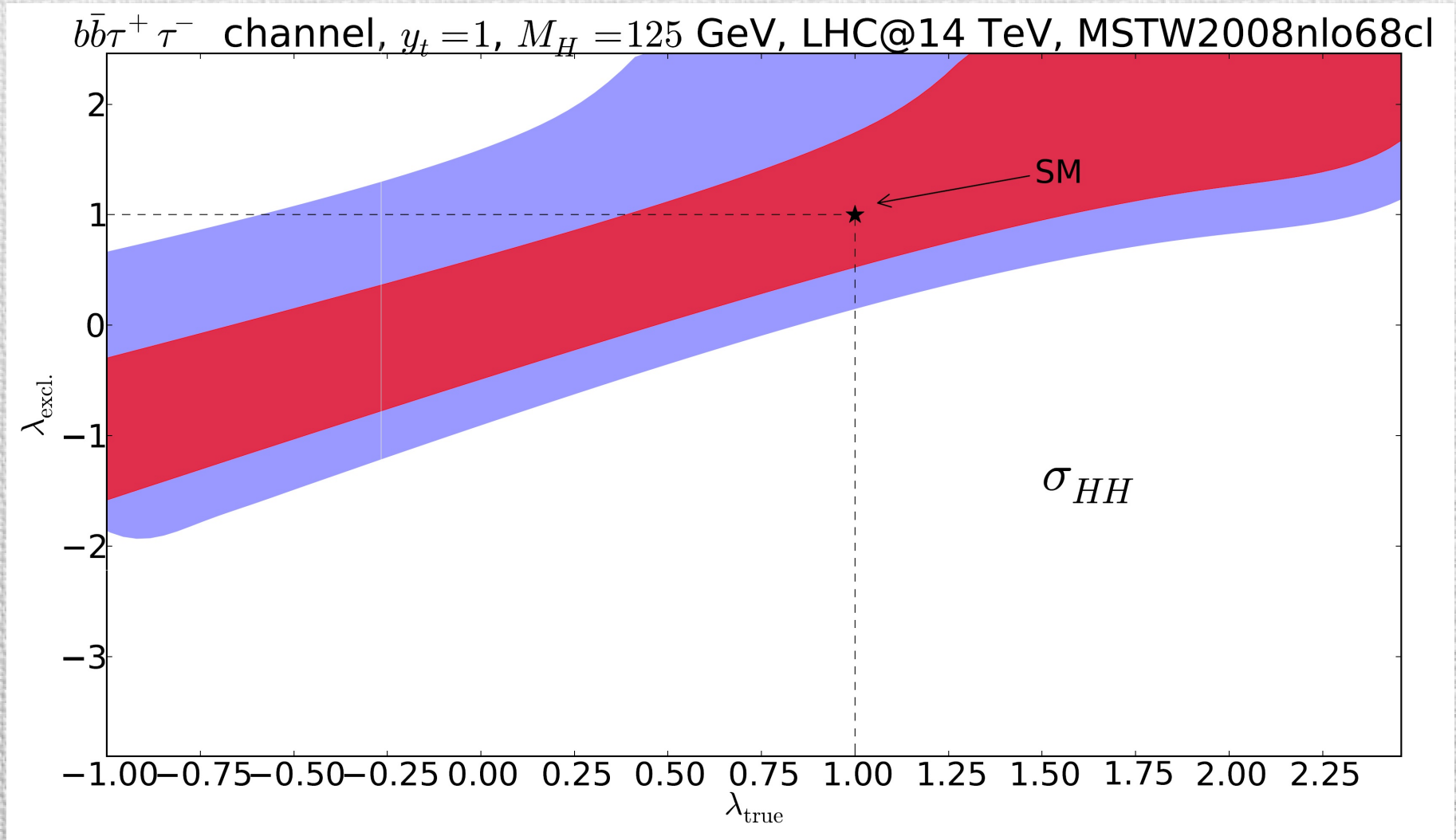
cross section itself:
20 % theoretical Error

*Expect additional errors - not present in C$_{HH}$*

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Measuring $\lambda$ using Ratios of Cross Sections

# Deriving Constraints



$b\bar{b}W^+W^-$ channel, $y_t = 1$, $M_H = 125$ GeV, LHC@14 TeV, MSTW2008nlo68cl

SM

$C_{HH}$

$\lambda_{\text{excl.}}$

$\lambda_{\text{true}}$

# Deriving Constraints



$b\bar{b}\gamma\gamma$ channel, $y_t = 1$, $M_H = 125$ GeV, LHC@14 TeV, MSTW2008nlo68cl

SM

$C_{HH}$

$\lambda_{\text{excl.}}$

$\lambda_{\text{true}}$

# Deriving Constraints



$b\bar{b}\tau^+\tau^-$ channel, $y_t = 1$, $M_H = 125$ GeV, LHC@14 TeV, MSTW2008nlo68cl

SM

$C_{HH}$

3000fb$^{-1}$

# Deriving Constraints

| Process | $600 \text{ fb}^{-1}$ $(2\sigma)$ | $600 \text{ fb}^{-1}$ $(1\sigma)$ | $3000 \text{ fb}^{-1}$ $2\sigma$ | $3000 \text{ fb}^{-1}$ $1\sigma$ |
|---------|----------|----------|----------|----------|
| $b\bar{b}\tau^+\tau^-$ | (0.22, 4.70) | (0.57, 1.64) | (0.42, 2.13) | (0.69, 1.40) |
| $b\bar{b}W^+W^-$ | (0.04, 4.88) | (0.46, 1.95) | (0.36, 4.56) | (0.65, 1.46) |
| $b\bar{b}\gamma\gamma$ | (-0.56, 5.48) | (0.09, 4.83) | (0.08, 4.84) | (0.48, 1.87) |

assume $\lambda_{\text{true}} = y_{t,\text{true}} = 1$, for disconnected regions only show below $\lambda_{\min} \simeq 2.43$

- Possible to constrain trilinear self coupling to be positive at 95% CL with 600fb⁻¹ using C$_{HH}$

- Comparable for $\boxed{b\bar{b}\gamma\gamma}$ to shape analysis $\lambda \in (0.26, 1.94) @ 600 \, \text{fb}^{-1}$

Baur, Plehn, Rainwater, hep-ph/0310056

actually also
$\lambda \in (2.98, 4.66)$,
optimistic asmpt

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Measuring $\lambda$ using Ratios of Cross Sections

# Deriving Constraints

| Process | 600 fb$^{-1}$ ($2\sigma$) | 600 fb$^{-1}$ ($1\sigma$) | 3000 fb$^{-1}$ $2\sigma$ | 3000 fb$^{-1}$ $1\sigma$ |
|---|---|---|---|---|
| $b\bar{b}\tau^{+}\tau^{-}$ | (0.22, 4.70) | (0.57, 1.64) | (0.42, 2.13) | (0.69, 1.40) |
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assume $\lambda_{\text{true}} = y_{t,\text{true}} = 1$, for disconnected regions only show below $\lambda_{\min} \simeq 2.43$.

- Possible to constrain trilinear self coupling to be positive at 95% CL with 600fb$^{-1}$ using C$_{HH}$

- Comparable for $b\bar{b}\gamma\gamma$ to shape analysis $\lambda \in (0.26, 1.94)$ @ 600 fb$^{-1}$

Baur, Plehn, Rainwater, hep-ph/0310056

- Improve predictions due to new channels

actually also $\lambda \in (2.98, 4.66)$, optimistic asmpt

- Combination of channels yields ~ +30% and ~ -20% accuracy with 3000fb$^{-1}$

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Measuring $\lambda$ using Ratios of Cross Sections

# Deriving Constraints

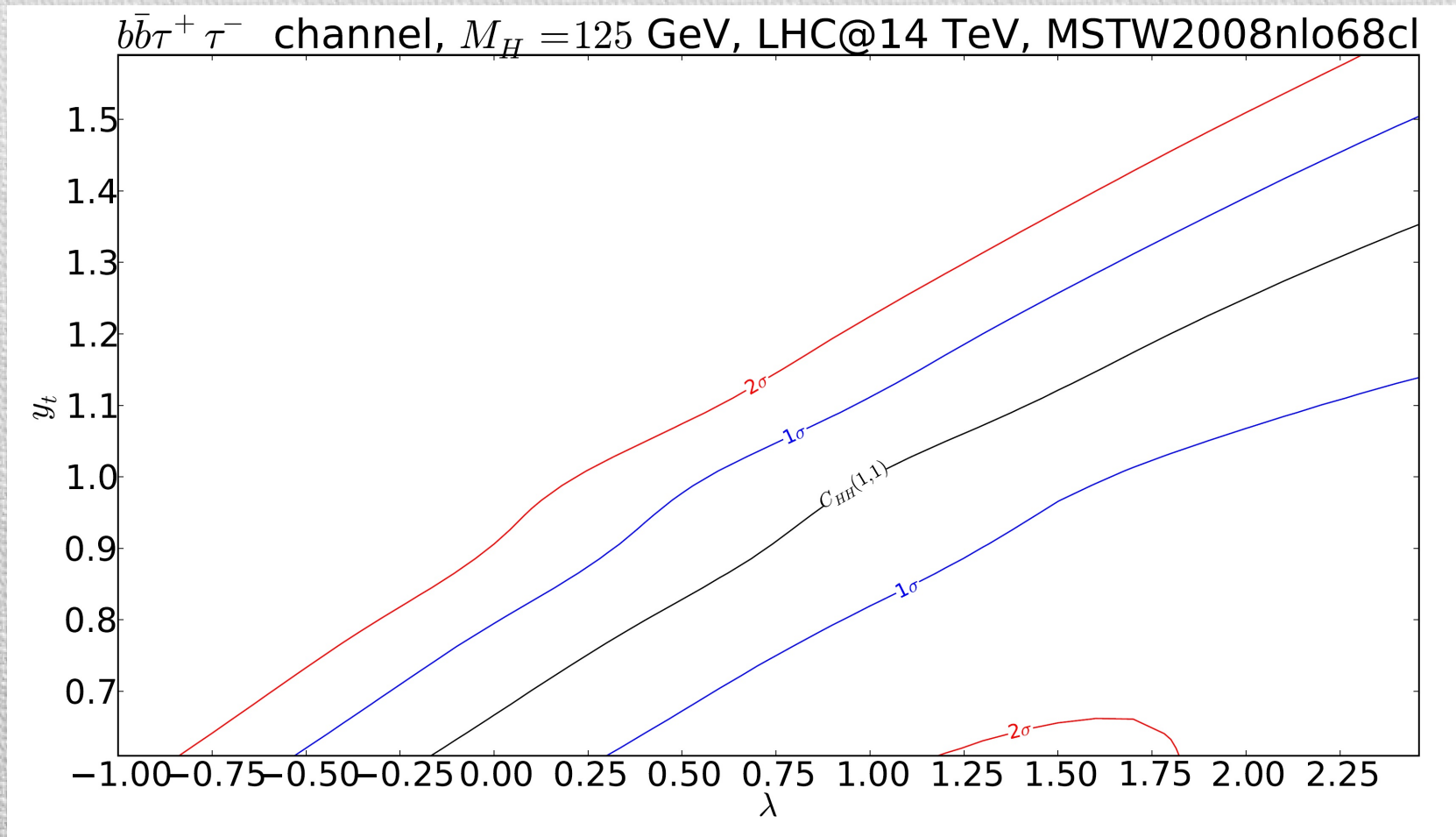| Process | 600 fb$^{-1}$ (2$\sigma$) | 600 fb$^{-1}$ (1$\sigma$) | 3000 fb$^{-1}$ 2$\sigma$ | 3000 fb$^{-1}$ 1$\sigma$ |
|---|---|---|---|---|
| $b\bar{b}\tau^+\tau^-$ | (0.22, 4.70) | (0.57, 1.64) | (0.42, 2.13) | (0.69, 1.40) |
| $b\bar{b}W^+W^-$ | (0.04, 4.88) | (0.46, 1.95) | (0.36, 4.56) | (0.65, 1.46) |
| $b\bar{b}\gamma\gamma$ | (-0.56, 5.48) | (0.09, 4.83) | (0.08, 4.84) | (0.48, 1.87) |

assume $\lambda_{\text{true}}=y_{t,\text{true}}=1$, for disconnected regions only show below $\lambda_{\min} \simeq 2.43$.

- Combination of channels yields ~ +30% and ~ -20% accuracy with 3000fb$^{-1}$

- Compare to ILC   <span style="color:green">ILC-TDR (2012, to be published)</span>

$$\sqrt{s} = 500\,\text{GeV}, \quad \mathcal{L} = 2000\,\text{fb}^{-1} \quad \text{~40\%}$$

$$\sqrt{s} = 1000\,\text{GeV}, \quad \mathcal{L} = 1000\,\text{fb}^{-1} \quad \text{~25\%}$$

# Variation with $y_t$

- $y_t$ only known to O(15%) after 300fb$^{-1}$ @14 TeV <span style="color:green">Peskin, 1207.2516</span>



$b\bar{b}\tau^+\tau^-$ channel, $M_H = 125$ GeV, LHC@14 TeV, MSTW2008nlo68cl

assume $y_{t,\mathrm{true}} = \lambda_{\mathrm{true}} = 1$, $\mathcal{L} = 600$ fb$^{-1}$

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# Variation with $y_t$



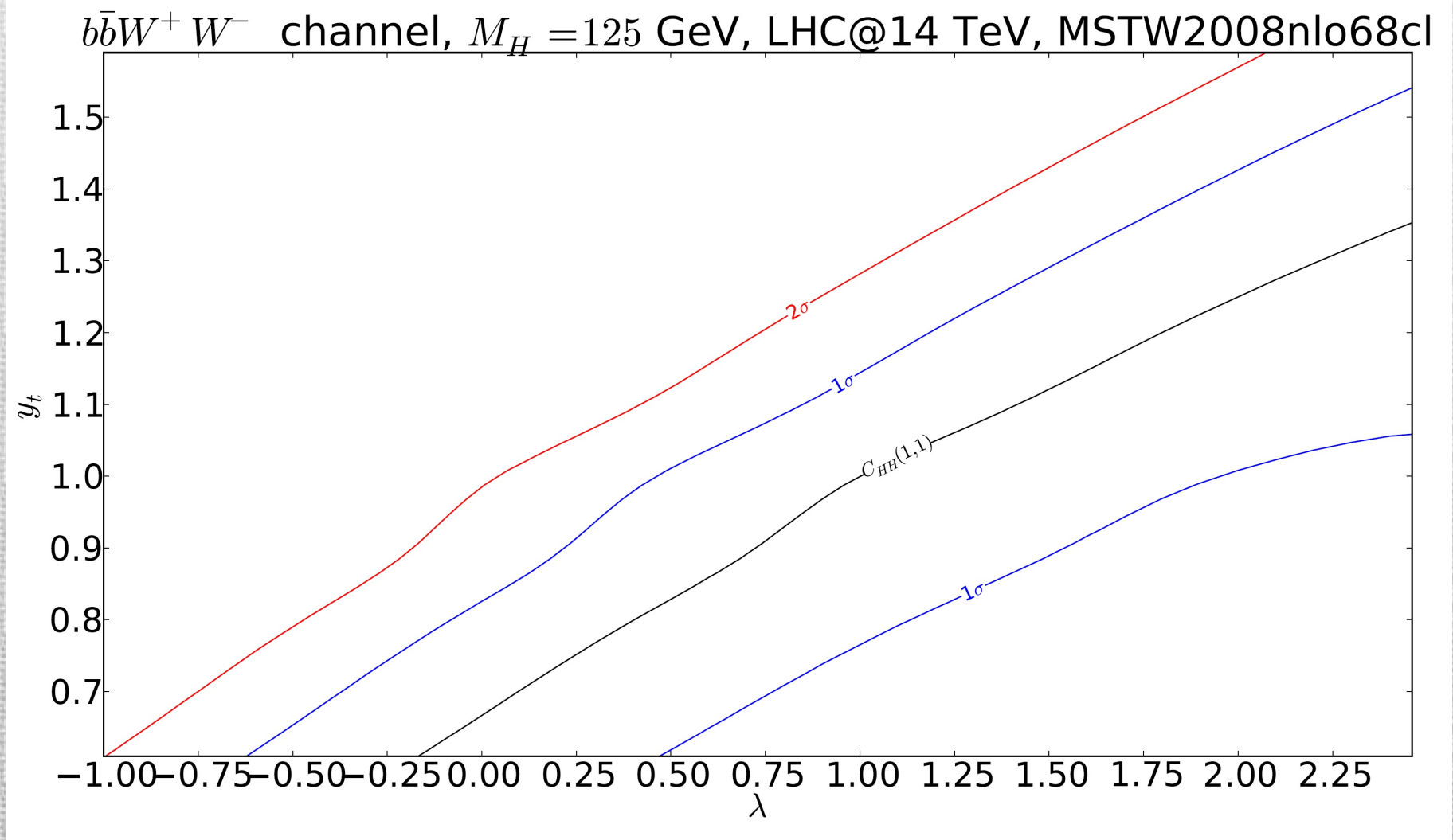$b\bar{b}\tau^+\tau^-$ channel, $M_H = 125$ GeV, LHC@14 TeV, MSTW2008nlo68cl
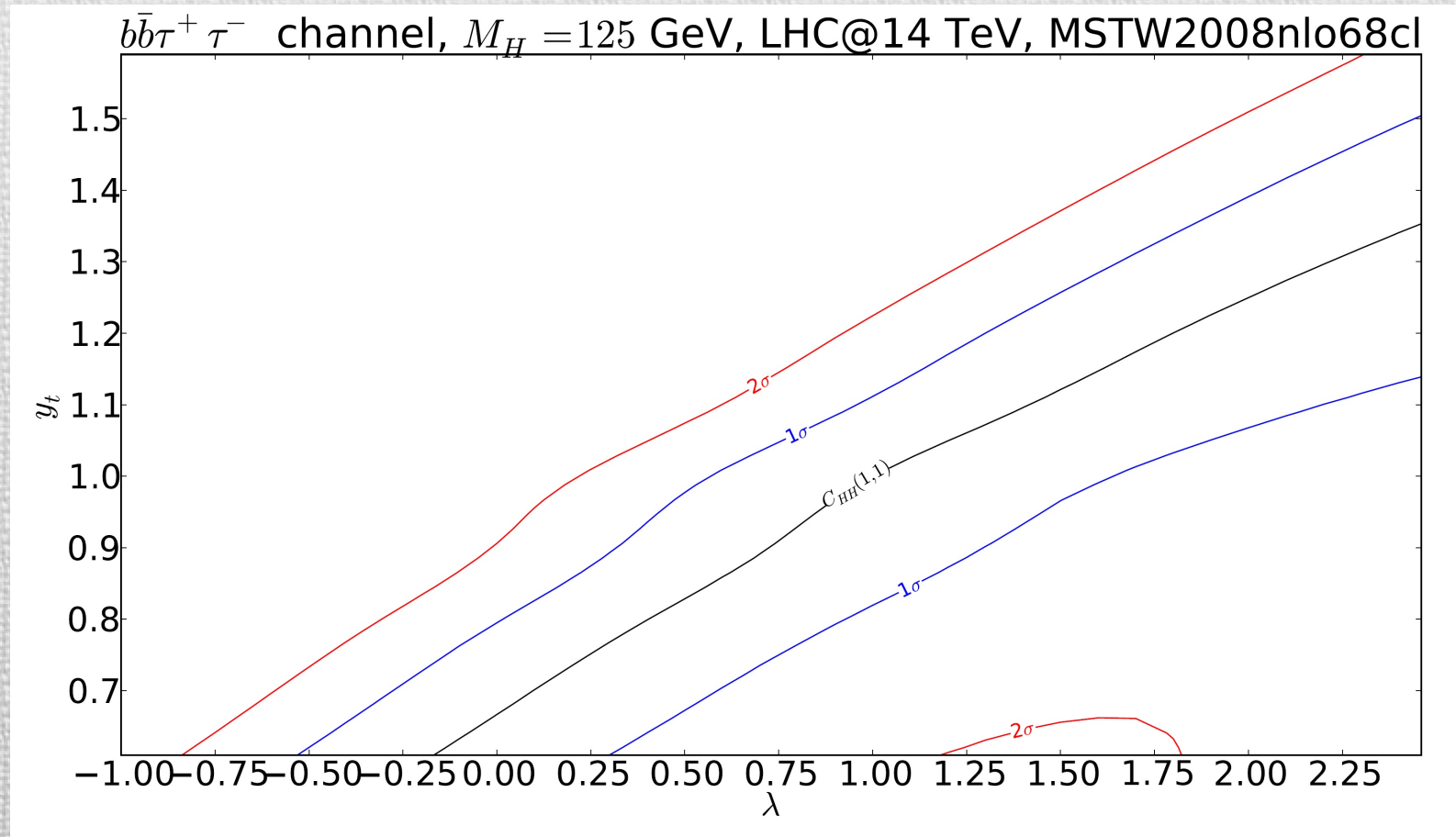
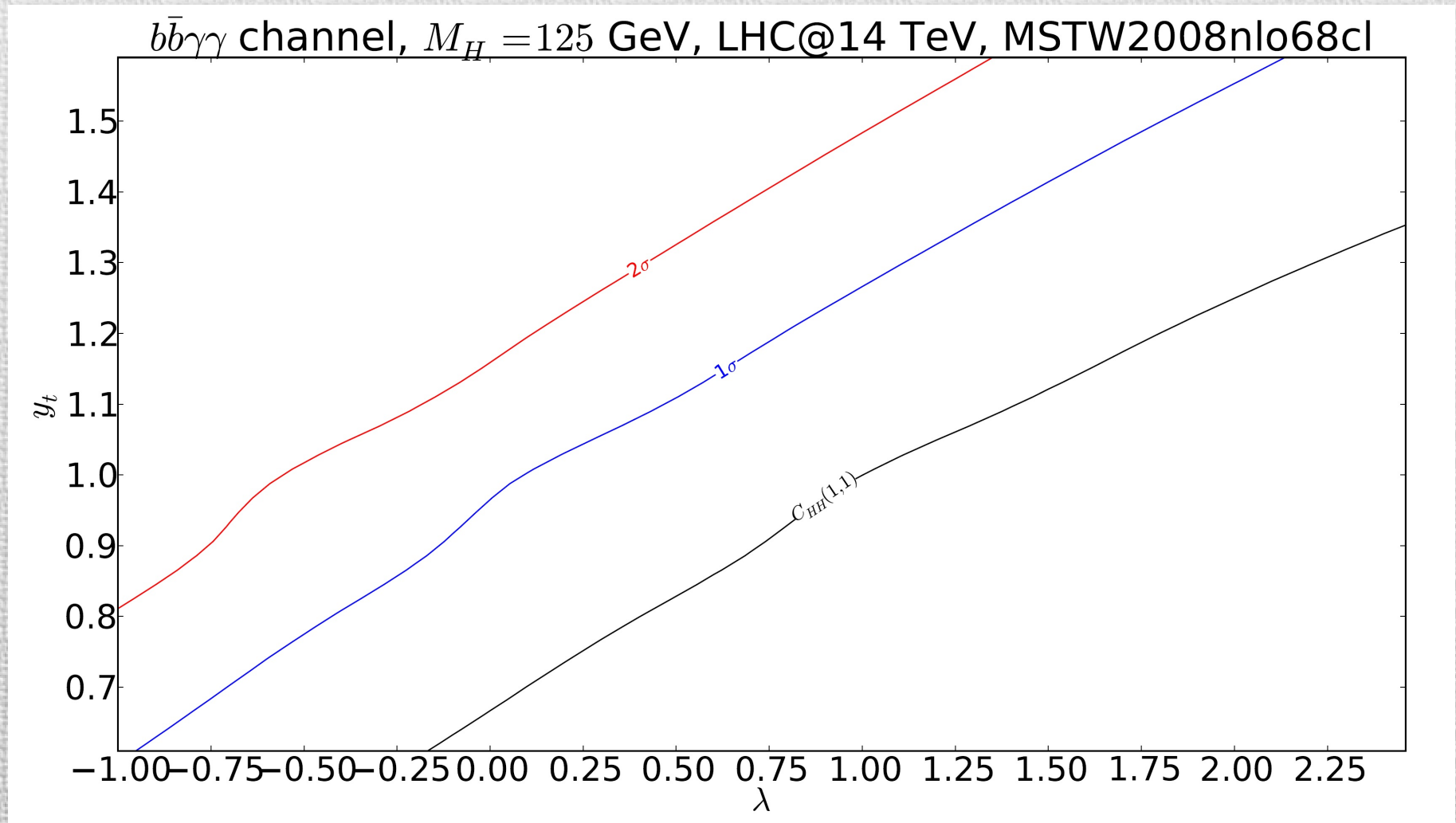$y_t = 0.85$ yields $\lambda \in (0.2, 1.1)$, whereas $y_t = 1.15$ implies $\lambda \in (1.1, \sim 2.4)$
$\implies$ accurate knowledge of $y_t$ is essential

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# Variation with $y_t$



$b\bar{b}W^+W^-$ channel, $M_H = 125$ GeV, LHC@14 TeV, MSTW2008nlo68cl

$2\sigma$

$1\sigma$

$C_{HH}(1,1)$

$1\sigma$

$y_t$

$\lambda$

# Variation with $y_t$



$b\bar{b}\gamma\gamma$ channel, $M_H = 125$ GeV, LHC@14 TeV, MSTW2008nlo68cl

$2\sigma$

$1\sigma$

$C_{HH}(1,1)$

# Outlook and Conclusions

# Outlook

- Do full „model independent" survey of double Higgs production, supplementing the SM Lagrangian with dimension 6 operators

- Use equations of motion to arrive at most appropriate basis for the analysis

# Outlook

- Employ precision constraints to further reduce the operator basis

- Use information from single Higgs production to constrain operators and derive expectations for double-Higgs production

- Study different scenarios

# Conclusions

- Examined theoretical error on ratio of dobule-to-single Higgs production cross section C$_{HH}$

- Using this ratio, derived expected exclusions on the trilinear H coupling in the $b\bar{b}\gamma\gamma$, $b\bar{b}W^+W^-$, $b\bar{b}\tau^+\tau^-$ channels

- Obtained the most precise expected determination of the Higgs trilinear self-coupling at the 14TeV LHC: -20/+30% achievable (in the SM)

- Good knowledge of top-quark yukawa important

- Outlook: Full operator analysis of HH production

# Thank you for the attention!